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Future propulsion & integration:
towards a hybrid-electric 50-seat regional aircraft

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Future propulsion & integration:
towards a hybrid-electric 50-seat regional aircraft

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DEM	Demonstrator, pilot, prototype	
DEC	Websites, patent fillings, video etc	
OTHER		

Dissemination	*Level*	
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Abstract

A series of workshops were organised in order to communicate the background and state-of-the-art of the key enabling technologies as well as the gaps in technology that should be addressed in order to achieve a hybrid-electric 50-seat regional aircraft by 2035-2040. The workshops were organised as follows:

- Energy harvesting, aircraft aerodynamics & aeroacoustics
- Thermal management
- Aircraft Design Specs
- Energy storage
- Hybrid-electric prime movers and electric motors
- Synthesis and synergies

The material presented in this document is extracted from these workshops. The intention is to provide a reference of the state-of-the-art in all key enabling technologies that will be further studied in FUTPRINT50. Aspects of certification have also been included.

1. Energy harvesting in aircraft

1.1 Introduction

Energy harvesting is the process by which energy is derived from external sources (e.g., solar power, thermal energy, wind energy also known as ambient energy), captured, and stored [1.1], thus making the system more sustainable.

For aircraft, there are various sources from which energy can be harvested. These sources can be divided into two categories based on the power output: low and high power output. Thermoelectric, piezoelectric, triboelectric, electromechanical, and photovoltaic are examples of low power output sources; waste heat recovery and regenerative braking are examples of high-power output sources.

1.2 High-power Sources

1.2.1 Regenerative Braking (RB)

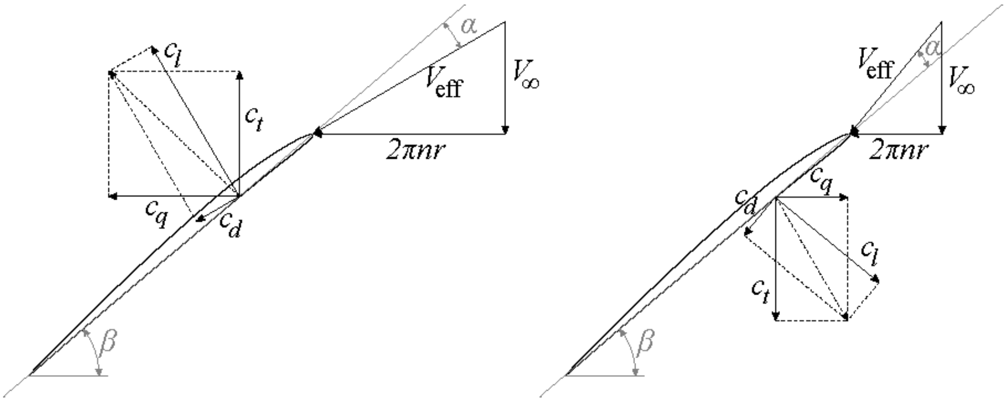
Braking is essential for any moving vehicle which is conventionally achieved by dissipating kinetic energy of the vehicle as heat using various means. The fuel economy of the vehicles can be improved by converting this kinetic energy of the vehicle into useful energy and this process is known as regenerative braking. The earliest use of regenerative braking was done in railways in 1890s. Cars equipped with regenerative braking were first proposed in 1967 [1.2]. Today, a lot of electrical cars, railways, and trams using the concept of RB can be found. Different designs use different ways to store the energy. In railways, regenerated electricity is fed back to the power supply. In cars, energy is stored in various ways: battery, supercapacitors, flywheels, as a compressed air in hydraulics, or is used to break water in fuel cells.

However, RB still is in research phase for aircraft, where it can be employed in two ways: using propellers as windmill or using landing gear-based motors during the braking phase.

1.2.1.1 Regenerative braking using propellers

Besides opportunities for advanced propulsion integration, electric propulsion also enables energy harvesting. During parts of the mission for which no power input is required, the motor(s) can be used as generator(s). As a result, energy can be recovered during flight, thereby reducing the energy consumption for a given mission. One way of harvesting energy is to use one or more propellers as airborne wind turbines during parts of the mission which do not require energy input. By operating the blade sections at negative angle of attack, the direction of the forces is inverted compared to the propulsive mode. This is sketched in Figure 1.1 for the case of a propeller at a given pitch angle. The negative torque corresponds to a negative power, which can be converted into electricity by the motor. This approach has been proposed before for gliders [1.3-1.6] and naval applications [1.7]. More recently, work by general-aviation manufacturer Pipistrel [1.8] confirmed the potential of energy recovery through regenerative propellers for an electric aircraft optimized for training missions. Besides potential applications to aircraft, energy-harvesting rotors are also being considered for airborne wind-energy systems, that use the rotors in propulsive mode for lift-off and hover [1.9].

Recent experimental and numerical studies at Delft University of Technology highlighted the low efficiency of conventional propellers in regenerative conditions [1.10, 1.11]. Typical efficiencies (regenerated shaft power / input power in the freestream) of about 10-12% were measured at an optimal blade pitch angle of 15 deg at r/R=0.7 [1.11]. This is due to a combination of induced losses due to suboptimal blade loading, and especially high profile losses on the positively cambered sections operated at negative angle of attack [1.10]. Optimization of the propeller will be required to enhance the regenerative performance without compromising the propulsive performance.



Propulsive mode

Regenerative mode

Figure 1.1: Velocity triangles at a fixed-pitch propeller blade section in propulsive and energy-harvesting modes

In contrast to the limited research focused on unducted rotors, energy harvesting in windmilling conditions has been addressed in more detail for rotors of turbofans [1.12-1.14]. Experimental, numerical, and theoretical studies confirmed the potential for power extraction in windmilling conditions, including consideration of the `negative rotation cases' with reversed rotational direction of the rotor. During free windmilling, the rotor blade loading typically features a mixed compressor/turbine operation [1.13,1.14], with positive loading (compressor operation) on the inboard part of the blade and negative loading (turbine operation) on the outboard part. At higher (negative) loading conditions, the whole blade is in turbine operation [1.13]. However, there are several differences compared to the propeller case. The presence of the casing in turbofan applications modifies the tip effects compared to the unducted propeller case. Furthermore, it causes an inlet distortion due to viscous effects [1.14]. Besides the direct effects on the rotor, for turbofan applications the flowfield is also affected by the stator response. During turbine operation, the stator vanes experience large negative angles of attack, which leads to stall [1.12]. This affects the overall mass flow rate through the engine and will have an adverse effect on the system performance. This is not a concern for propeller applications with a single blade row.

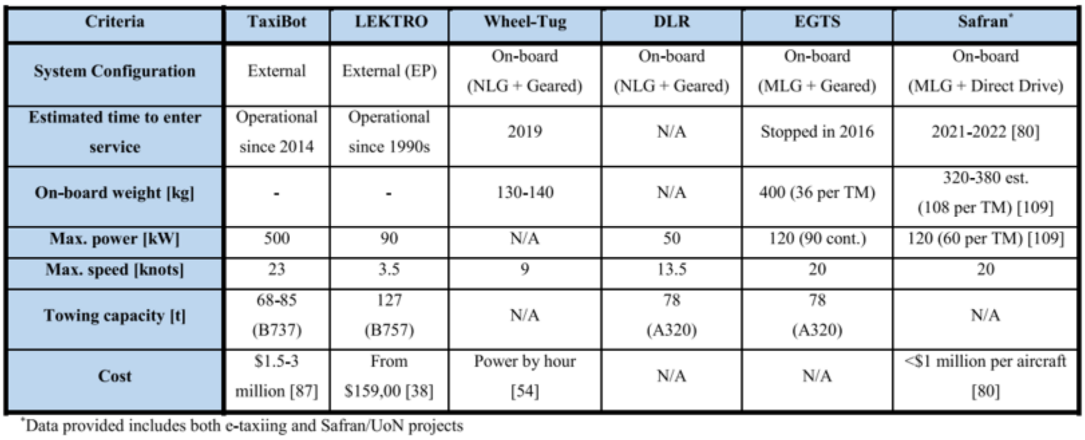
Considering the tight integration between the propulsion system and the airframe that is typical of electric aircraft designs, the use of propellers as energy harvesters will affect the overall vehicle performance. The performance depends strongly on the characteristics of the propeller slipstream. In propulsive mode, the enhanced dynamic pressure and swirl in the slipstream provide a performance benefit in case of inboard-up rotation [1.15,1.16]. If the propellers generate negative thrust, for example in an engine-inoperative condition with windmilling or feathered propellers, or in energy-harvesting mode, the slipstream will be markedly different from that when operating the propeller in the conventional propulsive mode. The lower dynamic pressure and swirl in the slipstream will cause a loss of lift on the wing, thereby adversely affecting the vehicle performance [1.10].

Previous work on energy-harvesting propellers has not adequately considered the consequence of negative propeller thrust on overall vehicle performance. The propeller in regenerative conditions will impose a slipstream that is completely different from the well-studied propulsive condition in terms of velocity gradients, pressure gradients, and vorticity. Research is required to understand the blade-loading and resultant slipstream characteristics of the isolated propeller in regenerative conditions, the regenerative performance at nonzero angle of attack, the noise emissions in regenerative conditions, and the interaction between the regenerative propeller and the airframe. These activities of WP3.3 and WP5.2 are focused on addressing these knowledge gaps.

1.2.1.2 Regenerative braking using landing gear-based motors

The working principle for this configuration is similar to RB in electric vehicles. In the driving mode, battery supplies the power to the wheel assembly and generates the torque in the same direction as the wheels. When braking is required, torque is in the opposite direction and the regenerated energy is used to charge the battery [1.17]. However, it should be noted that regenerative braking alone is not sufficient and needs to be used in combination with friction braking. Friction braking is required when sudden braking is required, or when vehicle needs to be still on a slope. Nevertheless, landing gear-based motors can be used for electrical taxiing, therefore, improving efficiency, reduced emissions, and noise. The use of RB for aircraft is still in research phase due to various complexities such as modification required for the integration, weight penalty due to battery and additional equipment, broad range of operating temperature, etc.

Onboard electrical taxiing systems (ETS) could be the first step towards RB. The existing state-of-art of ETS and their comparison is given in Figure 1.2 and Figure 1.3 respectively.



Criteria	TaxiBot	LEKTRO	Wheel-Tug	DLR	EGTS	Safran[*]
System Configuration	External	External (EP)	On-board (NLG + Geared)	On-board (NLG + Geared)	On-board (MLG + Geared)	On-board (MLG + Direct Drive)
Estimated time to enter service	Operational since 2014	Operational since 1990s	2019	N/A	Stopped in 2016	2021-2022 [80]
On-board weight [kg]	-	-	130-140	N/A	400 (36 per TM)	320-380 est. (108 per TM) [109]
Max. power [kW]	500	90	N/A	50	120 (90 cont.)	120 (60 per TM) [109]
Max. speed [knots]	23	3.5	9	13.5	20	20
Towing capacity [t]	68-85 (B737)	127 (B757)	N/A	78 (A320)	78 (A320)	N/A
Cost	$1.5-3 million [87]	From $159,00 [38]	Power by hour [54]	N/A	N/A	<$1 million per aircraft [80]

[*] Data provided includes both e-taxiing and Safran/UoN projects

Figure 1.2: State-of-Art ETS [1.18]

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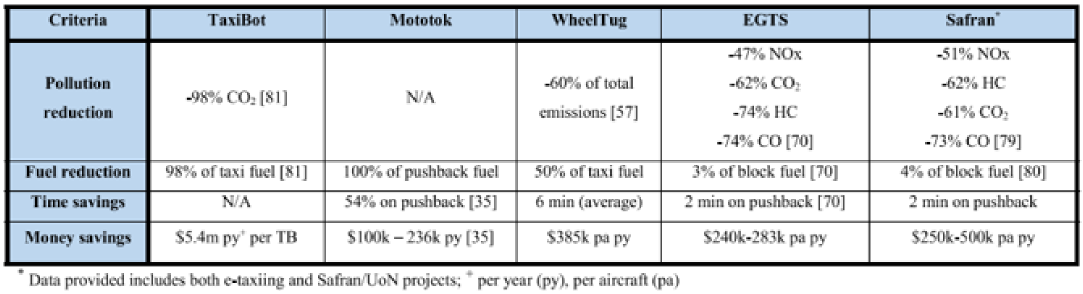

Criteria	TaxiBot	Mototok	WheelTug	EGTS	Safran[*]
Pollution reduction	-98% CO_2 [81]	N/A	-60% of total emissions [57]	-47% NOx -62% CO_2 -74% HC -74% CO [70]	-51% NOx -62% HC -61% CO_2 -73% CO [79]
Fuel reduction	98% of taxi fuel [81]	100% of pushback fuel	50% of taxi fuel	3% of block fuel [70]	4% of block fuel [80]
Time savings	N/A	54% on pushback [35]	6 min (average)	2 min on pushback [70]	2 min on pushback
Money savings	\$5.4m py[+] per TB	\$100k – 236k py [35]	\$385k pa py	\$240k-283k pa py	\$250k-500k pa py

[*] Data provided includes both e-taxiing and Safran/UoN projects; [+] per year (py), per aircraft (pa)

Figure 1.3: Potential benefits comparison for different ETS [1.18]

Reference [1.19] analyzed the impact of RB on Boeing B737-700 by implementing two 18-phase induction motors on main landing gear. It reports the fuel savings up to 65%. However, the weight of the modified system has not been taken into account in the analysis. In another research effort, RB was implemented on Airbus A321 main landing gear. The ETS powertrain was sized using data from 4 real taxiing cycles and the weight was determined to be 800 kg. It reported 15% energy recovery on average [1.20,1.21]. Studies at the aircraft level are missing in the literature and further research is needed.

1.2.2 Waste Heat Recovery

Internal combustion engines have an efficiency of 30-40%, meaning that 60-70% of the fuel energy is lost as waste heat [1.22]. Using waste heat to recuperate energy could lead to increased fuel efficiency and reduced emissions. Different cycles have been developed for this purpose such as Rankine cycle, Brayton cycle, Stirling cycle, Supercritical cycle and Trilateral flash cycle, [23]. In literature, Organic Rankine cycle (ORC) and Brayton cycle are found to be the most efficient options for waste heat recovery [1.23-1.25].

In 1976 (after the oil crisis), a research group tested ORCs on Mack 676 diesel engine to recover exhaust heat. The first configuration used Fluorinol-50 as the working fluid and a three-stage axial turbine as the expander. At the optimal performance of the system, 13% increase in maximum power and 15% increase in fuel economy was reported [1.26]. In the follow-up study, ORCs were tested with a 288-Bhp, Long-haul diesel engine. On average 12.5% reduction in fuel consumption was observed on high-way tests [1.27]. The interest in ORCs was renewed, when BMW in 2005 reported 15% improvement in engine performance using a Steam Rankine cycle. Honda also carried out tests with SRC in 2008. The maximum thermal efficiency of 13% was obtained at 23kW power. The maximum power obtained from expander was 32kW. Overall, 3.8% thermal efficiency was obtained at a constant speed of 62 miles/h, [1.28]. However, still, commercial ORCs are not available for vehicles in the market due to complex modification requirements and capital cost involved in the system.

Due to similar reasons, ORCs have not been implemented on the planes at the commercial level. Even at the research level, literature is limited regarding the integration of ORC on aircraft. In one of the research efforts, ORC was theoretically integrated into a CFM56 engine in the environmental control system which led to the elimination of pneumatic bleeds. This analysis predicts a fuel savings of 0.9-2.5% assuming that the ORC system adds a weight of 950 lbs per engine [1.29]. Another research group proved the feasibility of the idea by developing a 1D model [1.30] of the concept.

A modification in the Brayton cycle was proposed for application to turbocharged diesel engine. It results in fuel savings of 2.6% and 4.6% at high and low engine speed respectively [1.31]. It should be noted that no consideration of added weight was considered while estimating fuel savings. Reference [1.32] applied Brayton cycle to a passenger car resulting in 5.7% improvement in engine efficiency theoretically. In another study, different variations of the Brayton cycle were applied on a series hybrid electric vehicle. The intercooled Brayton cycle has been identified as the most optimal compromise between high efficiency and low integration complexity. The study reports 5.5% and 7% improved fuel economy in plug-in and self-sustaining configurations respectively [1.33].

1.3 Low-Power Sources

1.3.1 Thermoelectric Harvesting

Thermoelectric energy is harvested by using thermoelectric generators, devices that convert heat energy into electricity using the Seebeck effect, [1.34-1.35]. Thermoelectric generators have the advantage of being fairly compact, solid-state (no moving part), silent in operation and low maintenance requirements. They have a life cycle of about 5 years. Moreover, to apply thermoelectric generators on aircraft, no major changes are required in the design. Major drawbacks are low efficiency and low power density.

The maximum efficiency achievable for a thermoelectric with most advanced material, with Carnot efficiency of 50% turns out to be only 20%, [1.36]. The power density of thermoelectric systems varies with the temperature difference between hot and cold side. Reference [1.37] reports power density of 8 W/kg and 131 W/kg for ΔT of 10K and 40K respectively. On the other hand, reference [1.38] reports power density exceeding 80 W/kg for $\Delta \mathrm{T}_{max} = 120\ {}^{\circ}C$. In extreme conditions of $\Delta T = 500\ {}^{\circ}C$, reference [1.39] reports power density of 5.26 W/cm^2.

Due to these reasons, the use of thermoelectric generators in aircraft is limited to power wireless sensor nodes (WSNs) which are responsible for structural health monitoring [1.40]. Reference [1.41] tested thermoelectric generators using Phase changing material (PCM) on 28 real flights. The flights were categorised into typical (standard European short/mid-range flight) and atypical (very short time and altitude < 30000 ft). The average energy output of 22.8 J was recorded for typical flights, whereas only 2.1 J was harvested for atypical flights. In another investigation, a PCM thermoelectric generator was mounted on pylon aft fairing, [1.42]. The maximum harvested energy was reported to be 81.4 J with an efficiency of about 1-2%.

1.3.2 Thermionic Generators (TIG)

Thermionic generators are solid state heat engines which directly convert thermal energy into electrical energy using thermionic emission. The idea was first proposed by Schlichter in 1915, [1.43]. The first practical TIG was created in 1950s with an efficiency of 10-15%. However, due to complexity and low practical efficiency, TIG has been mostly limited to space applications, where the high cost could be offset by the savings in payload costs, [1.44]. The advancement in material science and nanotechnology has made possible to develop more efficient TIG and has renewed the interest in it. TIG are inherently more efficient than thermoelectric generators along with the good features such as compact, silent operation, higher power density and long lifespan. The main downside of thermionic generators is the requirement of high temperature heat source [1.45].

The work function[1] of emitter electrode should be as low as possible to increase the thermionic emission. However, for TIG to work, the collector work function should be even lower than emitter, preferably by at least 1 eV, [1.46]. There is a misconception in literature that the lower the work function, the better the performance of thermionic generators. Reference [1.47] shows that output voltage also needs to be tuned along with work function to obtain optimal performance.

One of the major challenges for TIG is that there are very few materials with low work function, [1.45]. Moreover, such materials tend to have low melting point, therefore, limiting the maximum achievable efficiency. Many researchers focus on developing techniques to lower work function. The main developments are advance coating techniques, surface nanostructuring, alkali metal adsorption, intercalation, graphene with tuned work function, etc., [1.44, 1.48, 1.49]. Besides lowering work function, there are other ways to enhance electron emission. Schottky barrier lowering, materials with negative electron affinity, doped carbon nanotubes, photon-enhanced thermionic emission are examples of such technology, [1.49].

Another problem which has impeded the development of thermionic generators is space charge effect. As the emitter emits electrode into the interelectrode gap, it becomes positively charged and tends to pull back the emitted electrons. This results in a cloud of electrons near the emitter surface and suppresses further electron emission. Various methods have been developed to mitigate the space charge effect such as Reducing interelectrode gap, positive compensation, using external electric and magnetic fields, negative electron affinity, etc., [1.44, 1.49, 1.50,1.51].

In general, higher the temperature of heat source, higher the maximum achievable efficiency. The efficiency of over 15% has been achieved with electrode temperature between $570\,^{\circ}C$ and $1300\,^{\circ}C$. The power density of 32 W/cm^2 has been achieved at high temperature ($> 1000\,^{\circ}C$) [1.45, 1.52]. However, the power density decreases quickly at low temperatures due to decreased emission and high work function. Therefore, thermionic generators can work efficiently at high temperatures compared to the thermoelectric generators which are operated at low temperature, [1.53]. Motivated from this idea, a thermionic-thermoelectric generator has been proposed in literature [1.54].

In the current state, thermionic generators are not being used for many applications. For application of this technology to aircraft, modifications in engine are required, as engine is the only component that can act as high temperature heat source for TIG. To the best of author's knowledge, no instance could be found in the literature, where TIG has been analysed or investigated for energy harvesting on an aircraft.

1.3.3 Electro-mechanical/Electro-hydrostatic Actuators

The effort of aviation industry to move towards electric aircraft has led to replacement of hydraulic and pneumatic actuation systems with their electric counterparts. These new actuators are placed under the category of Power-By-Wire (PBW) actuation. PBW has many advantages over the conventional Fly-By-Wire (FBW) actuation due to the elimination of pipes

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[1] It is the minimum amount of energy required to emit an electron from a solid to a point in the vacuum immediately outside the solid surface

and fluids such as increased safety and reliability, lighter weight, less volume, reduced complexity, reduced maintenance costs, leak-free operation, more efficiency, etc., [1.55-1.57]. Power-By-Wire actuation can be divided into three categories: i) *Electro-mechanical actuation* (EMA), ii) *Electro-hydrostatic actuation* (EHA), and iii) *Integrated actuator package* (IAP), [1.56].

The flight surfaces are continuously accelerated or decelerated during flight. During deceleration when motor speed is reduced, the electromagnetic torque is reversed in direction, which results in generation of electrical energy from inertia of motor load (similar to regenerative braking in cars), [1.58]. This regenerated energy from actuators is generally dissipated using damping resistors, [1.59, 1.60]. These damping resistors have to be rated for the worst case scenario, resulting in a heavy system. Moreover, thermal management is required due to heat generated in dissipation.

Allowing regeneration of energy on power system bus can help to get rid of heavy resistors and increase the efficiency of the system. However, such a system should be able to ensure power quality under all the operation conditions. Eight power system topologies have been recognized that can ensure power quality in the regenerative conditions based on central and local approach [1.57, 1.61-1.63]

In centralized approach, there is a common energy storage device (ultra-capacitor, battery, regenerative fuel cell, flywheel, etc.) or resistor for all the actuators. As suggested by the name, for the local approach an energy storage device or resistor for each actuator is present. The centralized approach is considered better in terms of savings in system size and weight. The competitive topology to centralized approach is returning energy back to the source. Though in the latter approach, no or little additional hardware is required, the regenerated power will influence the operation of the generator and requires modifications in the system.

Reference [1.63] compares different topologies by carrying out simulations. The authors concluded that when mission profiles become highly dynamic and generate large regenerative current, the EMA tracking is poor when energy is sent back to source. On the other hand, while using a centralized energy storage system, EMA tracking is affected and proves to be a superior topology. On the contrary, reference [1.57] concludes that returning power to the source does not affect the voltage control of the actuator and therefore, is best due to the weight savings and reduction in the number of components.

Another research group uses two-stage matrix converter for regenerated power management, which falls under the category of energy back to the source, [1.62, 1.64]. A real flight profile of a civil aircraft was used to test the performance of EMA. The results show excellent tracking of the flight profile. The regenerated power average was found to be negligible (1.93 W), however, the instantaneous peak of regenerated power reaches up to 260 W. The energy regenerated corresponding to this peak is calculated to be about 40 J.

Electro-hydrostatic actuators (EHA) has already reached a TRL[2] level of 9 and has been implemented for primary flight surfaces on Airbus A380 and Boeing 787 [1.55, 1.65]. Electro-mechanical actuators (EMA) is still on TRL level 6 and is used for secondary flight surfaces on Boeing 787. The main challenge for EMA is the risk of mechanical jamming that keeps it from

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[2] TRL - Technology Readiness Level

being applicable to primary flight surfaces. In the current state-of-art, resistor is used to dissipate the regenerated power. To the author's best knowledge, no instance could be found in the literature where regenerative power was stored or sent back to the source in a real flight.

1.3.4 Piezoelectric Devices

One of the most studied solution involves the use of piezo-electric material, which can convert mechanical vibration into electrical energy with very simple structure.

Piezoelectricity represents pressure electricity and is a property of certain crystalline materials such as quartz, Rochelle salt, tourmaline, and barium titanate that develop electricity when pressure is applied, this is called the direct effect and it can be used as a sensor or energy transducer. On the other hand, these crystals undergo deformation when an electric field is applied, which is termed as the converse effect that can be used as an actuator.

KIM ET AL. [1.66] in their works reports a review of vibrational energy harvester based on piezo-ceramic material. In this work, vibrational energy harvesting technology is highlighted as a permanent power source of portable electronic devices and wireless sensor network, the main problem is that the energy harvesters should be able to sustain under harsh vibrations and shocks. Furthermore, another limitation is that the obtained electrical energy from vibration is small, rectification and energy storing circuits should be able to activate in such a low power condition. Very interesting for aerospace application is the introduction of Hybrid-Electric Propulsion Systems (HEPS). The implementation of this technology presents a great challenge due to the insufficient energy densities and specific energies of electrical storage devices which increase strongly the

vehicle weight and volume. Energy harvesting technique is a very interesting opportunity for the developing of this technology in the future. Energy harvesting from renewable sources as opposed to relying on just one power source (Internal Combustion Engine) can enhance endurance and range performances, increase safety and decrease carbon emission [1.67]. The typical systems involve solar energy harvesting by exploiting photovoltaic panels on the wings and fuselage. More advanced energy harvesting concepts include the exploitation of naturally occurring vibrations caused by the propeller and by turbulence through piezoelectric generators.

The idea of use vibrational energy harvesting technology as a source of energy for wireless sensor is investigated even by HADAS ET AL. [1.68]. In this study a mechatronic approach for the development of the vibration energy harvester is presented. A vibration energy harvester consists of precise mechanical part, electro-mechanical converter, electronics and a powered application. It can be perceived as a mechatronic system and a mechatronic approach can be successful in order to design it. The principle behind the vibration energy harvesting is a resonance operation of an oscillating mass and consequent an electro-mechanical conversion of kinetic energy into electrical energy. The vibration energy harvesters use, generally, principles of a piezo-electric, magnetostriction, electro-static or electro-magnetic mechanical conversion. This mechanism is based on spring-less suspension of a moving mass M. The stiffness k is provided by repelled magnetic forces. This resonance mechanism is excited by ambient mechanical vibrations and it provides relative movement x of a magnetic circuit against a fixed coil (L, Rc). This movement induce voltage due to Faraday's law. This innovative approach can save time and total costs during development process of such vibration energy harvester.

Energy harvesting, combined with wireless sensors, may improve our ability to monitor and maintain critical structures. ARMS ET AL. [1.69] presents a structural health monitoring and reporting (SHMR) system for Navy aircraft utilization. It is well-known that one of the main problems in this application is that wireless sensors need energy to operate and batteries are a great problem in terms of volume and weight. A solution to this problem is to harvest and store energy from the environment – using strain, vibration, light, and motion – to generate the energy for sensing and communications. Combined with strict power management, smart wireless sensing networks can operate indefinitely, without the need for battery maintenance. In this work fundamental is the role of the energy harvester electronics feature nanoampere comparator that allows the wireless sensor to draw current only when the stored energy is high enough. The flight test showed that this energy harvesting strain and load sensor can operate continually, without batteries, even under low energy generation condition. By continuously monitoring the rotating component loads, these wireless nodes can track metal fatigue, and estimate remaining life.

MAGOTEAUX ET AL. [1.70] investigated the benefits of the integration into a small unmanned air vehicle (UAV) of energy harvesting system. Both solar and piezo-electric technique were analyzed and compared with a reference vehicle (reference has to be intended as a vehicle without energy harvesting system). To study the effects of these technologies on a small UAV the approach is centered around thermodynamics and involves either entropy generation or energy destruction.

In [1.71] a study on the piezoelectric application in aircraft is reported. They investigate the energy produced by 4 piezo-electric harvesters in the frequency range typical of an aerospace panel during flight. The devices were mounted on a vibrated plate of aluminium of dimensions $387\ x\ 254\ x\ 0.6\ mm$. The results show that in order to power an aerospace SHM system currently, an energy harvesters must have size between $71cm^2$ and $5.1m^2$ or between 0.02 and $12kg$ of PZT but that this measure are going to be substantially reduced in the future due to the reduction in power requirements of an typical SHM system. The use of solar cell technology and piezoelectric technology incorporated into the aircraft to recharge the batteries when not in flight is a promising solution to this problem. The aircraft is assumed to have the ability to stay at a target location for an extended period of time with the harvester devices implemented.

The energy harvesting UAV used solar cells to recharge its batteries while still at the target location. The first analysis of the two aircrafts showed that the energy harvesting aircraft generated much less entropy but was unable to stay in the air at the target as long as the reference aircraft. As the target distance increased, the performance of the two devices began to converge. On the other hand, the piezoelectric generators replaced the landing gear in two configurations: cantilevered and curved beam designs. The results showed that the cantilevered design was more suitable for lower frequency input vibrations, but the curved beam design was the better of the two. These two designs with the inclusion of the solar array were successfully demonstrated to be beneficial for a small UAV.

ERTURK ET AL. [1.72] propose the use of a L-shaped beam-mass structure as a new piezoelectric energy harvester configuration with the capability of produce a broader band harvesting system. The commonly used piezoelectric energy harvester configuration is a cantilevered beam with one or two piezoceramic layer [1.70]. Cantilevered energy harvester is located on a vibrating host structure and the dynamic bending strain induced in the piezoceramic layer(s) results in an alternating electric potential difference between the electrodes covering the piezoceramic layer(s). The L-shaped structure can be tuned to have the first two natural frequencies much closer to each other (on the frequency axis) when compared to the conventional cantilevered beam case. Such effect is a favorable feature in the sense of broadband energy harvesting for random or varying-frequency excitations. They suggest using it as a landing gear for UAV applications by paying attention to the size and weight limitations of the UAV in the design process of the L-shaped energy harvester. The primary resonance of interest is the dominant excitation frequency and it might be the operating frequency of a vibrating base on which the UAV lands during a mission. This solution seems to improve the flight time of UAVs during the mission and powering their sensors and global positioning units.

Energy harvesting is an attractive technology for mini UAVs because it offers the potential to increase their endurance without adding significant mass or the need to increase the fuel system size. The work of ANTON ET AL. [1.73] investigates the possibility of harvesting vibration and solar energy in a mini-UAV. It is proposed that piezoelectric vibration harvesters and photovoltaic solar harvesters should be incorporated into the aircraft design in order to actively harvest vibration and solar energy. The focus is on quantifying the energy available for harvesting from both aircraft vibrations and ambient sunlight and to perform a proof of concept study on piezoelectric energy harvesting in UAV applications. Flight test of an RC aircraft were carried comparing the performance of piezoelectric harvesting and photovoltaic harvesting in UAVs. Preliminary tests show that during a 13 minutes flight, the solar panels could charge a $170\ mAh$ battery to 14% capacity and the piezoelectric patches could charge the EH300 $4.6\ mJ$ internal capacitor to 70% capacity. The main difference between the two systems is that every time the aircraft is in flight, the piezoelectric patches will harvest energy, however, the solar panels will only harvest energy when exposed to light. This gives piezoelectric harvesting an advantage when flying at night or in cloudy conditions.

Another interesting possibility is the utilization of thermoelectric energy harvesting systems as energy source for autonomous structure health monitoring (SHM) system. Thermoelectric generators (TEG) for energy harvesting use the available temperature difference and makes wireless sensors fully autonomous. The autonomous power source combines aircraft specific outside temperature changes with a thermoelectric generator (TEG) and a heat storage unit. The temperature difference generated with the latter component artificially at the TEG is used to power the sensor node by thermoelectricity. A TEG can be attached directly to the fuselage and be combined with a phase-change material (PCM) heat storage unit to create a temperature gradient during take-off and landing, thereby generating electrical energy. An aircraft-specific thermoelectric generator module consisting of a PCM heat storage and a TEG element has been designed, simulated, and tested [1.74, 1.75]. Both simulations and experimental results verify that an autonomous aircraft power source is possible to feed sensor nodes for purposes such as structural health monitoring. The energy harvesting power supply worked reliable and the generated energy is sufficient to power a sensor for three additional flights. Energy directly generated by the TEG was approximately 6 mWh with a total conversion efficiency of the power management of about 20% [74].

Even, Pearson et al. [1.76] focused on the application of energy harvesting system for SHM system for aerospace application. They investigate both a piezo-electric transducer and a TEG. The former con be utilized to generate power from a dynamic strain, the latter can be used to extract power from a thermal gradient. The implementation of an autonomous SHM system at the design stage could allow for more optimized structures in safety critical areas which would reduce weight. This would lead to improved aircraft performance, lower fuel consumption and greater maximum range which would reduce the running costs of an aircraft. The experimental tests on the piezoelectric transducer has been carried out in a frequency vibration range between 20 and 400 Hz using a sinusoidal driving signal, at each particular frequency the load resistance was altered from $1M\Omega$ to $5k\Omega$ in order to gain the maximum power transfer. For the TEG a numerical simulation has been carried out by the "mypelt" tool. Both energy harvestings techniques show a real potential for powering an SHM system, however in reality these devices would not be able to directly power a SHM system due to the varying nature of the sources. Therefore, a further power management system would be necessary in order to provide a stable power source from the dynamic nature of the energy sources in order to power an SHM system.

1.3.5 Photovoltaic Devices

Photovoltaic technology is the most known of renewable technologies and uses solar panels composed of cells to convert energy from the sun into a flow of electrons.

There are three classes of solar cells that differ in materials and manufacturing:

- Single junction
- Multiple Junction
- Thin Film Technology

For many years, this technology has faced two challenges: reducing production costs and increasing conversion efficiency that is still not very competitive, but some more innovative technologies seem to be able to make PV more affordable [1.77].

1.3.5.1 Crystalline Silicon Wafers

This is the oldest and best known technology and dominates the photovoltaic market. Its implementation is simple in fact it consists of a large p-n doped area with an efficiency of around 20%.

Its high cost is due to the materials used and its efficiency decreases by 0.5% every degree Celsius [1.77].

Several studies have been aimed at reducing costs and improving efficiency, for example the back-contact solar cells allow to increase the absorption surface thanks to the posterior positioning of the contacts while maintaining a simple production design [1.78].

Thanks to other improvements such as surface textures and anti-reflective coatings, large low cost solar cells have been obtained that reach an efficiency of 21.5% [1.78, 1.79].

Higher efficiencies (24-25%) have been achieved by prototypes such as PERL (Passivate emitter, rear locally-diffuse) and PERT (Passivated emitter, rear totally-diffused) which approach the theoretical maximum achievable efficiency of 30% [1.80] but require surface processing (pyramids reverse on the absorption surface) and materials which increase production costs.

1.3.5.2 Thin Film Technology

In the last decade this technology has been developed that does not require the expensive materials of crystalline silicon wafer, in fact it uses new inorganic semiconductors such as amorphous (non-crystalline) multi-junction silicone or cadmium telluride [1.77].

Despite low production throughput, low efficiency, stability problems and cost being comparable to crystalline Si cells, the cell technology has the advantage of a simple and standardized manufacturing process for integrated modules on hard and flexible substrates [1.81].

The forecast is that thin film technology will take a large part of the photovoltaic market in the future due to the fact that efficiency does not decrease as fast at high temperatures as for crystalline SI cells, the average module manufacturing cost is constantly decreasing (more rapidly than Crystalline SI) and that thanks to the wide choice of materials it is possible to obtain a competitive product with SI such as amorphous silicon cells and Thin-film polycrystalline silicon on glass [1.82].

1.3.5.3 Multijunction Solar Cells

This technology achieves efficiencies of 35-40% [1.83, 1.84] and is expected to reach 50% in the next 10 years.

Recently, nanotechnology, innovative deposition and growth techniques, and novel materials opened routes for reaching higher performances and for developing very low-cost devices such as organic based PVs [1.77].

The solar cell with multiple junctions allows the use of 3 - 5 semiconductors which each absorb a range of the solar spectrum reducing thermal losses. This technology does not lose efficiency at high temperatures and requires reduced production costs but has been known for less time and not yet fully developed.

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2 Thermal management

2.1 The challenge of Thermal Management in aircraft

Definition of Thermal Management:

Thermal Management is the ability to manage heat transfer between heat sources and sinks to control the temperature of aircraft subsystems/components in order to achieve comfort, safety and efficiency.

In order to provide thermal management of aircraft systems and spaces (i.e., electronic equipment, cabin compartments, ice protection systems, etc.), thermal management systems (TMS) shall be necessary. Generally speaking, TMSs transfer heat from one aircraft element (heat source) to another (heat sink) through the circulation of thermal fluids that get in thermal contact with the heat sources and heat sinks. TMS architectures may comprise fluids in single phase (i.e, brines) or phase change (i.e., refrigerants, water, others) and a combination of cooling technologies such as liquid cooling systems, vapor cycle systems, heat pipes, air cooling systems, cryogenic cooling systems, etc.

Figure 2.1: The role of TMS in aircraft

2.2 Current TMS

Current aircraft design manages heat according to aircraft requirements such as the need to heat surfaces (wing, tail, engine inlet, windscreen) for ice protection purposes, cabin heating and cooling, equipment cooling, and external instruments heating (air data sensors, drains). Figure 2.2: Main heat sources, consumers and sinks in modern civil aircraft shows an example of conventional aircraft typical heat sources, consumers and sinks that TMS are designed to manage in order to attend systems and aircraft requirements such as temperature control, efficiency (fuel consumption), comfort and safety. The main systems and related functions are:

- Pneumatic system extracts compressed airflow from the engines, decreases its temperature and pressure and directs it to the air conditioning and ice protection systems;
- Air conditioning system receives the compressed airflow from the pneumatic system, decreases its temperature and pressure in an air cycle machine (ACM) in order to provide heating and/or cooling for the pressurized compartments (cabin, cockpit, cargo bays, electronic bays);
- Ice protection system receives the compressed airflow from the pneumatic system and directs it to the leading edges of wing and tail;
- Windshield and sensors heating use electrical resistances.

The pneumatic, air conditioning and ice protection systems manage the airflow extracted from the engine compressor in order to perform their respective functions. Together they are called the aircraft Air Management System (AMS).

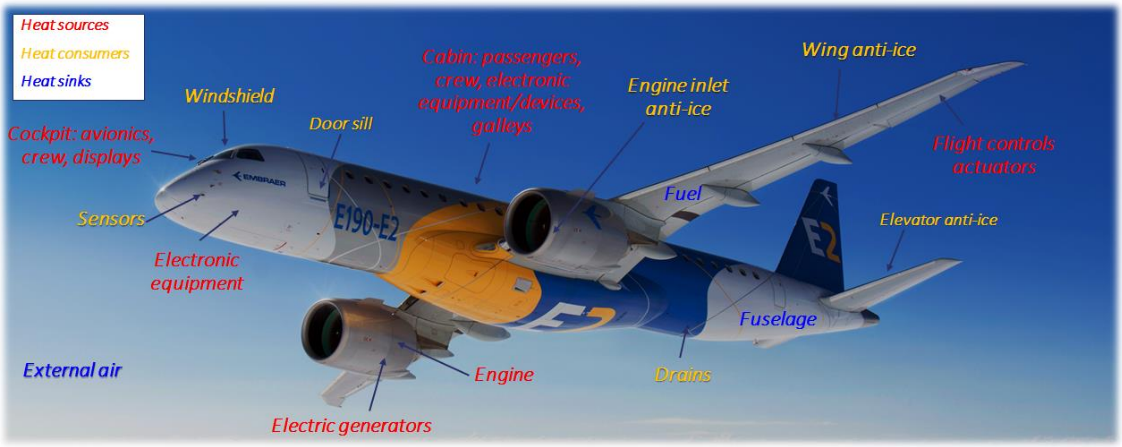

Figure 2.2: Main heat sources, consumers and sinks in modern civil aircraft

2.3 Challenges of TMS for future HEA: trade-offs, opportunities and synergies

2.3.1 Main challenges created by Electric and HEA

Although there is a lot of research and technology development aiming at increasing the efficiency of the new electric/electronic equipment such as batteries, converters/inverters, controllers, motors, etc., what happens is that, as the power required to feed these equipment (that ultimately generate thrust to move the aircraft) is increasingly high (1 MW order of magnitude), unusual very high heat dissipation will result. This definitively “much higher than conventional” power train heat loads, both in steady state or transient (peak) conditions, have to be managed by the TMS.

Consequently, higher impacts on aircraft drag (due to ram air inlets and outlets required to cool the heat exchangers for instance), weight, power consumption and costs of Electric and HEA thermal management systems are expected. In order to make the project feasible, it’s paramount to research innovative TMS architectures that decrease these aircraft level impacts.

Other relevant aspect of TMS are safety, certification and operational aspects. Regarding safety, one of the main challenges is to contain a battery thermal runaway. Essentially, when this event started it cannot be ceased, so as a result large amounts of heat and smoke are generated. Hence, the TMS design shall predict requirements to decrease the aircraft level impacts of a battery thermal runaway. The certification of future batteries must be better discussed between OEMs and authorities, in a way that the equivalent level of safety is achieved when compared to a conventional aircraft. In that sense, considerations of systems and TMS failure modes, redundancy, MTBF and others must be performed. Regarding operations, it is mandatory to consider the reliability and maintainability of the TMS, GSE (Ground Support Equipment), spare parts and operational limitations.

The increase of electronic equipment in aircraft design has been observed over the years. Also, electronic equipment has been evolving to miniaturization and increased power consumption (and dissipation) designs, which lead to an effect of increasing the heat dissipated by area (and volume). Therefore, the miniaturization of electronics increases the power density (W/kg) and heat dissipation density (W/m^2, W/m^3, W/kg) of equipment imposing a challenge to the TMS. Also, electronic equipment is usually installed in electronic compartments or bays which become high condensed electronics regions.

According to these characteristics of Electric and HEA, TMS may need non-conventional solutions which are described in the following chapter. Needless to say, some of these solutions shall bring challenges and associated risks to an aircraft design, on integration, safety, reliability, maintenance, etc., especially those related to the UK-UK (unknowns unknowns).

These risks can be identified early in the preliminary design phase of aircraft development due to lack or non-reliable information available in these phases (ex.: aircraft systems architecture and capacity, efficiency, costs, mean time between failure, etc.). Consequently, trade-studies are important to understand the impacts of each solution at the aircraft level.

2.3.2 Main opportunities & synergies

Due to the amount of heat dissipation of HEA equipment, high impacts on weight, drag and power consumption are expected from TMS/cooling systems at the aircraft level. Therefore, integrated TMS approaches are important to decrease these impacts. Some strategies can be explored within the TMS, such as thermal energy reuse, energy harvest, intelligent use of aircraft heat sinks, and thermal accumulators. Some examples are (not exhaustive):

- Thermal energy reuse: circulation of a hot stream of fluid (ex.: ethylene glycol water mixture) through a heat exchanger of an aircraft zone that needs to be heated (passenger cabin, door sill, galleys);
- Energy harvest: use of temperature gradients to generate an electrical potential through Seebeck effect (taking advantage of temperature differences between motors, thermal engines, and fuselage);
- Intelligent use of aircraft heat sinks: circulation of a hot stream of fluid to skin heat exchangers, fuel tanks;
- Thermal accumulators: use phase change materials in order to accumulate heat (ex.: during high transients) or "cold" (ex.: at high altitude) and use them for heating or

cooling in specific flight phases (ex.: ground operations). Or bring thermal accumulators on board before flight.

2.4 Technology state of art highlights and gap analysis

2.4.1 Liquid Cooling Systems

The great advantage of liquid cooling systems is the greater capacity for transporting heat when compared to air or gases. This is due to the higher thermal capacity (mass flow multiplied by the specific heat) of the liquid, which can cool equipment with higher power densities [2.1]. In addition, due to the higher density of the liquid, the transport lines become smaller. On top of that, for being (for all practical purposes) incompressible, liquids require very low power to be pumped. Generally, the heat transfer to the liquid can be direct or indirect. Direct transfer offers less thermal resistance since the liquid gets in direct contact with the equipment to be cooled. In this case, the liquids must be non-electrically conductive. In the indirect case, the heat transfer between liquid and equipment is done by heat conduction using a cold plate. The great advantage of this method is that the equipment can be removed in a maintenance operation without having to drain the liquid, which makes the maintenance process easier and faster. The main components of a liquid cooling system are pump, heat exchanger, filter, accumulator or reservoir, bypass for some components (such as the pump and the filter), overpressure valve, valves for supplying and draining the liquid, temperature control system and heater. Cooling fluids can be thermo oils, ethylene glycol water mixture (EGW), propylene glycol water mixture (PGW), Polyalphaolefin (PAO) and others. Maintenance of liquid cooling systems is important in order to avoid leaks, fluid contamination, and fire potential.

Some characteristics of liquid cooling systems are:

- The temperature operation limits depend on the fluid properties;
- Performance depends on the environment heat sink temperatures;
- Present low power consumption;
- Can be integrated to other aircraft cooling systems such as cabin and e-bay air cooling, skin heat exchangers and heat pipes / thermosyphons.

TRL today is high (>7) for aviation, being used in the Boeing 787 and military applications, as examples.

2.4.2 Thermal Accumulators (Phase Change Materials)

Phase change materials (PCM) are substances such as graphitized carbon, sodium acetate, water and others that absorb or release large amounts of heat over a defined temperature range due to the phase transition, from solid to liquid or vice versa. Using this technology, the PCM can provide cooling and heating to batteries, motors or electronic devices, when the material reaches its specific phase change temperature. Referred as latent heat storage materials, the PCM are considered highly efficient thermal storage devices. Some characteristics of PCM are:

- Each kind of PCM has a defined temperature range when the material changes the state or phase;
- The thermo-physical properties should be accurate for the correct objective;
- The PCM will have different solid and liquid phase thermophysical properties;
- Chemically stable, the PCM can be in service for a long time;
- Noncorrosive, nonflammable and safe;
- Phase change materials (PCM) can be integrated to other cooling systems such as air cooling, Vapor Cycle Systems, especially to absorb high heat fluxes during equipment transient (peak) conditions.

TRL today is medium [4-6] for aviation.

2.4.3 Cryo-cooling Systems

In order to operate high temperature superconducting (HTS) components, it is necessary to reliably maintain their temperature level in the range of 65 to 75 K [2.2]. Cryogenic cooling systems can be designed with the use of Stirling and Gifford McMahon thermodynamic cycles, which present relatively high efficiency. Another approach to the development of cryo-systems is the use of Powerful Pulsating Pipes (Q-drive, USA). An important advantage of pulsating pipes is the almost complete absence of moving parts which allows to dramatically increase the reliability and the interval between maintenance operations. However, they are inferior compared to cryo-refrigerators based on Stirling cycles in terms of cooling power. The most promising cryo-refrigerators shall use turbochargers and turboexpanders based on the Brighton cycle. TRL today is low [1-3] for aviation.

2.4.4 Pumped two phase systems (e.g. vapor cycle systems, evaporative cooling)

Vapor cycle systems are closed loop systems that circulate refrigerant fluid via tubing, which absorbs and removes heat from a device and rejects to a heat sink. The refrigerant fluid has specific properties under varying pressures and temperatures, and the most common refrigerants are R22, R134a and R410a. [2.3-2.5]

The main processes of vapor cycle systems are: compression of the refrigerant by a compressor, heat rejection of the refrigerant to a condenser, expansion of the fluid through an expansion device (such as a valve), and heat absorption by the refrigerant in an evaporator. The refrigerant fluid is a two-phase vapor-liquid mixture, that have different temperatures and pressures at the condenser and evaporator.

Vapor cycle systems have higher power consumption but can achieve low temperatures to cool electrical components in an aircraft and provide air conditioning to the passengers and crew. Vapor cycle systems provide a much higher coefficient of performance than air cycle systems. This technology allows a broader cooling envelope since the heat is rejected at temperatures below ambient (ex.: external air on ground).

Vapor cycle systems can be integrated to other cooling systems such as liquid cooling loops, air cooling, heat pipes and others.

TRL today is high (>7) for aviation, being used in the Boeing 787 as examples.

2.4.5 Air cooling (e.g., fans, air cycle machines, ram air)

Generally, air cooling is accomplished by flowing air around/inside the heat loads. The air flow can be natural or forced convection. Forced convection is accomplished by fans inside equipment or compartments. [2.6-2.9]

Also, air cycle systems (such as bootstrap systems) are used in order to decrease the cooling air temperature below ambient, through a compression, cooling and expansion cycle. Thereunto, a high-pressure sources of air (ex.: air flow bled from engine compressors, electrical blowers) are used.

Ram air cooling is achieved at flight by scoop (duct) directing the external airflow to heat exchangers. However, aircraft ground operations are supported by fans. There is limitation of using air cooling: ram air temperature is limited by the external air temperature.

Air cooling can be integrated to other cooling systems such as liquid cooling loops, vapor cycle systems, heat pipes and others.

TRL today is the highest (=9) for aviation, being used in many aircrafts.

2.4.6 Skin heat exchangers (e.g. fuselage heat exchangers)

The aircraft skin act as a heat exchanger transferring heat to the ambient air. Skin heat exchangers (SHX) can be used mainly at flight conditions when the external air presents adequate heat transfer properties. [2.10-2.12]

SHX can be constructed by fuselage and/or wing panels that circulate the heat transfer fluid (liquid or air) through internal channels.

The SHX can be part of a cooling system as an alternative or complement of ram air heat exchangers.

Skin heat exchanger can be integrated to other cooling systems such as liquid cooling loops, air cooling, heat pipes and others.

Fuel, liquid coolant can be used as working fluid.

TRL today is high (>7), as Airbus currently adopts it.

2.4.7 Absorption refrigerator

Absorption refrigerator is evaporation-absorption-regeneration system that uses a heat source to provide the energy needed to drive the cooling process. The refrigerant is cooled during its absorption by the absorbent. [2.13]

In aircraft with HEP associated heat from the gas turbine engine can be used for operation. It is possible to use the absorption refrigerator as a pre-cooler in the thermal management system.

Working media of absorption system of aircraft thermal management system can be: Ammonia ($NH3$) + Water (H_2O), Lithium bromide ($LiBr$) or Lithium chloride ($LiCl$) salt + Water (H_2O).

There are several benefits of absorption technology: utilization of waste heat of the gas turbine, no ozone-depleting components, the absence of massive moving parts and vibration, low cost of maintenance. But there are drawbacks that need to overcome to shift TRL: low thermal dynamic, presence of harmful components of ammonia-type machine, low energy efficiency. However relatively low cooling coefficient (0,6 - 0,8) can be compensated by the lack of power consumption.

TRL today is medium (4-5) for aviation. Probability of shifting TRL before 2030 is not high.

2.4.8 Joule-Thomson effect

The gas-cooling throttling process is commonly exploited in refrigeration processes such as air conditioners, heat pumps, and liquefiers. The air changes its temperature when it is forced through the valve while keeping it insulated so that no heat is exchanges with the environment. No external work is extracted from the air during the expansion. Free throttling of air leads to decrease of its pressure and temperature with constant enthalpy. [2.14, 2.15]

Air throttling supplied to the heat exchangers of the ECS system to a pressure value close to overboard pressure will increase the efficiency of heat removal in the heat exchanger and raise the energy efficiency of the ECS.

This effect is largely achieved at cruising altitude.

The throttling due to the flow resistance in supply lines and heat exchangers is a source of losses that limits the performance.

TRL today is medium (4-5) for aviation. Probability of shifting TRL before 2030 is medium.

2.4.9 Vortex tube

The vortex tube, also known as the Ranque-Hilsch vortex tube, is a mechanical device that separates a compressed gas into hot and cold streams. The vortex tube has no moving parts.

In aircraft thermal management the movement of air from the air blower will allow to get the output airflows of pre-cooled and heated air for the air-cooling preparation system.

The benefits of vortex tube are: absence of refrigerants, simple construction, no moving parts and thus high reliability, high thermal dynamic, the use of the tube can reduce the power consumption of the cooling system in the ECS air preparation system, flexible regulation is possible to optimize the parameters of the cooling-heating system overall. The drawbacks are: need to use high compressed gas to obtain low temperatures, relative low energy efficiency. However isentropic energy conversion efficiency that is now about 50% can be potentially shifted to 80%. [2.16-2.19]

TRL today is low [not higher 3] for aviation, but can be shift to [6-7] easily before 2030 year.

2.4.10 Magnetocaloric effect

Magnetocaloric effect – the ability of a magnetic material (e.g., gadolinium) to change its temperature and entropy under the influence of a magnetic field. This effect can be used to build a magnetic refrigeration system in the aircraft TMS with HEP. That type of aircraft will probably generate a high magnetic field. [2.20-2.21]

A magnetic refrigeration system uses commonly a rotating wheel structure that consists of a wheel containing segments with gadolinium powder. The wheel heats up when it crosses the magnetic field. This heat must be withdrawn. When gadolinium exits the magnetic field, the material is further cooled and thus cool the blower air directly or using a secondary coolant system. Magnetic refrigeration has high thermodynamic efficiency and it is 20-30% more efficient than vapor-compression refrigeration system. Wide operation temperature range provides wide utilization. Relatively high output power in superconducting magnets system provides high efficiency when this technology is used with superconductivity.

The benefits of magnetic refrigeration are: low environmental hazard, long life cycle, silent, vibration free design, flexibility of technology. TRL today is low [not higher 3] for aviation, but can be shift to [6-7] before 2030 year.

2.4.11 Thermionic energy converter

Thermionic energy converter is a heat engine that generates electricity directly using heat as its source of energy and electron as its working fluid. Despite having a huge potential as an efficient direct energy conversion device, the progress in vacuum-based thermionic energy converter development has always been hindered by the space charge problem and the unavailability of materials with low work function [2.22]. A thermionic wave generator produces electrical power directly from heat, which drives a thermionic emission process (Edison emissions) using no moving parts or working fluid, which minimizes entropy generation in the system.

As a stand-alone system it can replace internal combustion engines (ICEs) across a range of applications, from household power through transportation. Integrated into combined heat and power (CHP) systems it can transform power generation at a range of scales (e.g., from kW–MW). The thermionic wave generator enhanced efficiency over prior thermionic systems derives from Space Charge's work to-date on addressing thermal and electromagnetic loss mechanisms.

Projections from mini-prototype data & engineered models indicate:

- 65% overall conversion efficiency
- > 2x times improvement in realized prior art
- Theoretically up to 90% with an optimized system
- Operational temperature ~ 800 °C.

Low cost via wafer-fabrication and advanced material technologies.

Energy and power densities similar to gas turbines, without working fluid, moving parts or maintenance requirements.

TRL today is low (3-4) for aviation. Probability of shifting TRL to (6-7) before 2030 is medium.

2.4.12 The thermoelectric effects: Seebeck effect and Peltier effect

The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice versa via a thermocouple. Seebeck effect is the buildup of an electric potential across a temperature gradient. The potential difference across the ends for two dissimilar series-connected conductors is proportional to the temperature difference between hot and cool contacts. Peltier effect is an energy transfer when an electric current pass through the junction of two dissimilar conductors, from one conductor to another. Peltier effect can be considered as the back-action counterpart to the Seebeck effect. The efficiency of the device that generates heat as a by-product can be increased by recovering the energy lost as heat. The lesser the temperature of the hot side, the greater the amount of power will be produced. [2.23-2.25]

The value of the resulting thermo-EMF in a small temperature range depends only on the material of the conductors and the temperatures of the hot and cool contacts.

Value of thermo-EMF:

- copper-constantan: $\varepsilon \approx 4{,}28$ mV / 100 °C
- chromel-alumel: $\varepsilon \approx 4{,}10$ mV / 100 °C

Thermo-EMF of “classic” metals is very small (on the order of several mV/K), but for semiconductors it can exceed 1000 mV/K.

Thermoelectric generators using liquid on the cold side perform better than any other cooling method and produce significantly more net additional power. However, bismuth telluride is the standard semiconductor material that can improve the efficiency of thermoelectric generators at low temperatures.

TRL today is low (2-4) for aviation. Probability of shifting TRL to (6-7) before 2030 is medium.

2.4.13 Passive Systems (e.g. heat pipes, thermosyphons, vapor chambers)

Heat pipes, defined as devices that transfer heat by a process of evaporation and condensation of a fluid circulating within a sealed cavity, exist in a variety of sizes and configurations. They all have a region where the working fluid is evaporated (evaporator) and a region where it is condensed (condenser). The fluid circulation can be driven in a number of ways, most commonly by capillary forces in a porous wick (heat pipes), but also by gravitational forces (thermosyphon). Therefore, the heat transfer is performed by the evaporation and condensation of the working fluid [2.26].

Size and weight reductions are crucial requirements for aeronautical devices, leading to high power dissipation rates per area. Heat pipes/thermosyphons/vapor chambers are devices adequate for high transfer rates (100 to 1000 more than convective air) on small surfaces, therefore, adequate for large power density equipment. Also, require low maintenance and no power consumption since are passive devices.

Heat pipes can be integrated to other cooling systems such as liquid cooling loops, VCS evaporators, etc. Also, at flight the fuselage is submitted to low temperatures and high convective heat transfer coefficients, which make perfect conditions for transferring the heat of the heat pipes condensers [2.27].

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3 Aircraft Design Specs

Aviation is changing, and so are future aircraft concepts. Many full- or hybrid-electric aircraft designs are drawn on paper and some technology demonstrators as well as enablers are planned.

Starting with the concepts on paper, many different technologies are incorporated in various design approaches. MIT's D8.5 and H3.2 concepts feature boundary layer ingestion (BLI) in an effort to reduce fuel consumption in combination with specially shaped fuselages [3.1]. Another BLI concept is the Propulsive Fuselage from the German research lab Bauhaus Luftfahrt where a turbofan engine is added in the rear in addition to the conventional layout [3.2]. According to Bauhaus Luftfahrt further savings could be achieved by replacing it with an electrical motor [3.3], such a design is NASA's STARC-ABL [3.4–3.6]. Another interesting concept is a mid-range aircraft from the German Aerospace Centre DLR. It uses a rear BLI fan and a canard instead of a conventional tail [3.7].

The ONERA Dragon also features BLI and combines it with a distribution of propulsors which are located under the wing [3.8]. A collaboration between NASA and ESAero is the ECO-150R where distributed propulsion is located within the wing itself [3.6]. Another design with distributed electric propulsion (DEP) is the DLR regional jet [3.7]. The last concept is the Airbus E-Thrust [3.9]. It also combines BLI with some minor distribution of the propulsors.

One of the many projects in the category of enablers and technology demonstrators is the NASA X-57 Maxwell [3.10] which is set up in four stages. It uses high-lift DEP combined with two cruise wingtip propellers (WTP). In stage three, both these propellers are tested without the high-lift propellers which will be added in the fourth stage. Another demonstrator will be the Airbus/Daher/Safran joint undertaking EcoPulseTM [3.11] which is a cruise DEP configuration. Together with Rolls Royce, Airbus also planned the larger scaled hybrid-electric demonstrator E-Fan X [3.12] where one turbofan was replaced by a 2 MW electric motor. During the corona crisis, the project was cancelled [3.13]. Regarding hydrogen, the only large-scale demonstration project was the TU-155, a modified TU-154 in which one engine burned liquid hydrogen and later liquid natural gas.

The Eviation Alice [3.14] and the Zunum aircraft family [3.15, 3.16] are two projects with a commercial aim. The first is fully electric with WTPs and a BLI pusher propeller at the aft fuselage. It was close to its maiden flight before it was set back by a fire that partially damaged the prototype [3.17]. The Zunum family consists of the small six- to twelve-seat hybrid-electric aircraft ZA10, the 50-seat regional ZA50 and the biggest 100-seat aircraft ZA100 [3.15, 3.16]. Currently, it went silent around the company, as Zunum ran into financing troubles in late 2018 [3.18, 3.19].

With these designs in mind, novel propulsion concepts such as WTP, DEP and BLI were investigated in FUTPRINT50 and their influence on aircraft design was captured. Furthermore, disruptive technologies such as hydrogen aircraft and structural batteries were discussed. To round up the aircraft design, different propulsors were rated with regard to the TLARs of FUTPRINT50.

In addition, this workshop was grouped with the vision of FutPrInt50 and potential future missions for this type of aircraft. As this is part of WP 2 and thus D2.1, it is not included in this deliverable.

3.1 Boundary Layer Ingestion

BLI describes propulsors that are placed into the boundary layer of the airplane. The mechanism behind it can be split into two parts: "The first effect comes from the elimination of the wake defect itself through ingestion, while the second effect comes from the reduction of jet kinetic energy required associated with the first effect" [3.1]. For installation, there are two general possibilities, the first is the full-annular (or symmetric installation), the latter is an asymmetric installation [3.20]. Figure 3.1 shows a possible configuration featuring both variants – asymmetric on the wings and full-annular at the aft fuselage.

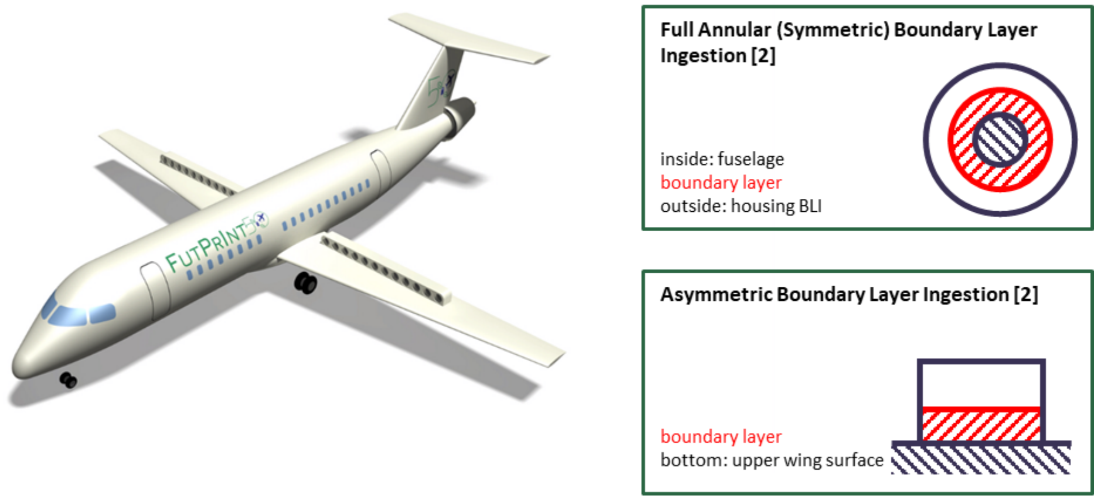

Figure 3.1: FutPrInt50 BLI configuration [USTUTT]

Installing BLI propulsors on the wing instead of propellers allows a low wing configuration because there are no issues regarding ground clearance. The additional mass of the BLI fan at the tail shifts the centre of gravity (CG) of the airplane backwards. To have a stable airplane, the wing is also moving backwards and thus a bigger tailplane is required to account for the reduced lever arm.

The radar chart in Figure 3.2 is used to quantify the benefits of the shown aircraft configuration by BLI. It contains qualitative guesstimates from the consortium members on selected, most influential parameters.

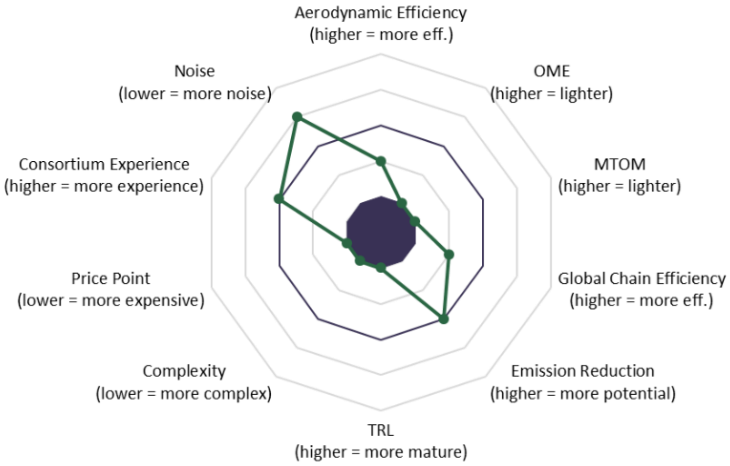

Figure 3.2: Radar Chart Guesstimate BLI

Aerodynamic efficiency is mainly decreased by the propulsors on top of the wing and the increase in wetted area. The overall mass of the airplane (OME & MTOM) is increased by the added systems as well as the number and length of the power cables. The quantity of wires also leads to a decrease in global chain efficiency. It is believed that the emissions of this airplane are similar to a configuration without BLI. The only positive value is the noise emission which is reduced by the shielding function of the duct. Still questionable is the influence of the turbulent boundary layer which might create additional noise sources. Also this flow requires special distortion tolerant fans, the probability of their TRL reaching level 4 by 2025 is estimated to be 90 % for the D8.5 and 80 % for the H3.2 configuration [3.1]. GREITZER ET. AL. calculated the contribution by BLI in reducing the Payload Fuel Energy Intensity [3.21] to be 2.57 % for the D8.5 and 9.52 % for the H3.2 [3.1]. For the STARC-ABL configuration, 12 % savings in start of cruise for TSFC are estimated which convert to 9 % block fuel reduction for an economic mission and 15 % for the design mission [3.5, 3.6].

Alternative configurations without ducts, for example the centre pusher propeller of Eviation Alice, are possible and reduce the mass penalty. Overall, it might be beneficial to separate the power systems of the main propulsion on the wing and of the BLI fan in the rear. By that, the amount of wiring is reduced. Also, emission free solutions, like batteries or fuel cells, are thinkable as separate driver of the aft BLI fan.

3.2 Wing Tip Propulsion

An aircraft with WTP has a propulsor mounted at each wing tip. The idea is to reduce drag and increase efficiency by interacting with the tip vortex [3.22–3.25]. A possible configuration is shown within Figure 3.3.

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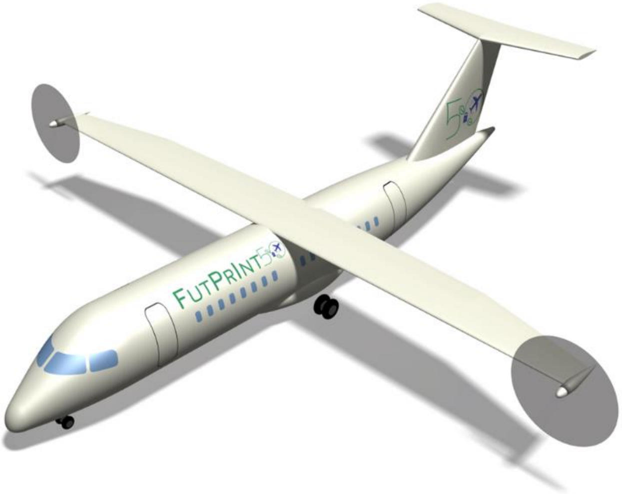

Figure 3.3: WTP configuration [USTUTT]

In this configuration the ground clearance is limited which is especially critical for crosswind landings. Furthermore, to tackle asymmetric thrust in a One-Engine-Inoperative (OEI) condition the size of the vertical tail plane is increased drastically. Alternatively, additional propulsors have to be installed that provide enough thrust alone, so both engines can be shut down simultaneously in case one fails. Again, the Eviation Alice is an example for such a configuration. Probably the most promising aircraft design including WTPs will be a combination with other propulsive devices.

The radar chart for this configuration is shown in Figure 3.4. As explained before, the aerodynamic efficiency is expected to increase due to the interaction with the tip vortex. The mass of the airplane is similar, as there are no additional propulsors. Additional wiring will increase the mass, but the positioning of the propulsors at the tip, on the other hand, will decrease the wing bending moment and with that the mass. In combination with the aerodynamic improvement, the increased global chain efficiency will result in emission reductions. Noise and cost will remain about the same, even despite the increased complexity by the added wiring.

MIRANDA ET. AL. has shown that the benefit from a WTP is higher if the tip region is higher loaded. This results in decreasing potential gains for high aspect ratios (AR). A wing with an AR of 12 reduces induced drag by 16 % at a lift coefficient of around 1.25. The same wing with an AR of 6 generates this reduction at a lift coefficient of roughly 0.6. [3.22]

Similar results on wing level can be found in [3.23]. Depending on the flow solver, BORER ET. AL. have calculated a drag reduction for the X-57 Maxwell of 7–18 % [3.26]. At an angle of attack (AoA) of 3°, experimental data of PATTERSON AND BARTLETT show a reduction in drag of roughly 10 % [3.27].

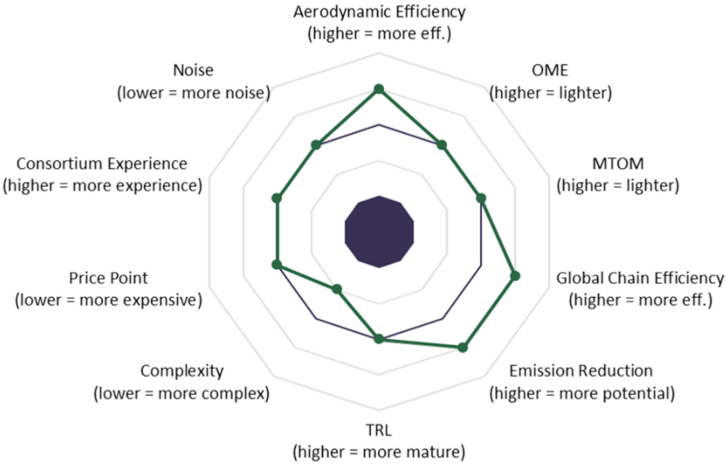

Figure 3.4: Radar Chart Guesstimate WTP

3.3 Distributed Electric Propulsion

For DEP, the main propulsion units are split into several electric motors which are distributed along the wing. This could be on the leading or trailing edge as well as over or under the wing. Several different benefits can be achieved and two general design choices, the cruise and the high-lift configuration, are available. In both cases, DEP could be described as WTP with additional propulsion on the wing.

3.3.1 Cruise Configuration

The cruise configuration is characterized by multiple similarly sized propulsors that are active in all phases of flight. If the overall power train is sized appropriately, then the redundancy is increased [28]. Furthermore, the propulsive efficiency is increased while noise is decreased by the reduction in propeller loading [3.28, 3.29]. Figure 3.5 shows a possible configuration for a regional aircraft with cruise DEP.

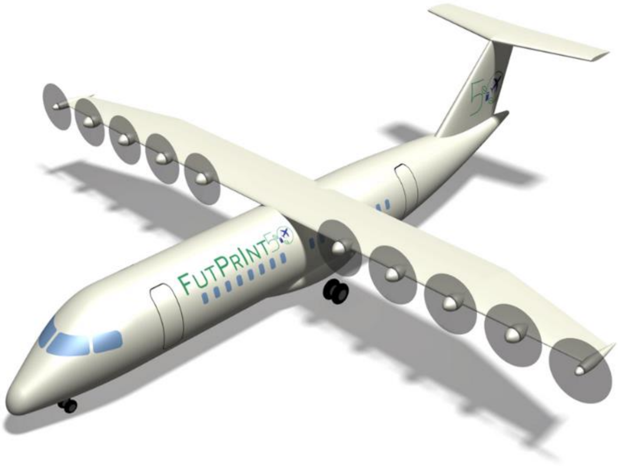

Figure 3.5: DEP Cruise Configuration [USTUTT]

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To increase ground clearance, a high wing configuration is selected. By choosing a T-tail, the horizontal tailplane is kept out of the propeller flow as well as out of the downwash produced by the wing. Each propeller accelerates the air around the wing which increases dynamic pressure. This allows for a smaller wing area.

According to Hepperle a reduction in required shaft power of 10–20 % can be achieved if the wing chord is reduced by 20 %. Another benefit of this concept is the possibility of maneuvering due to differential thrust which allows for a reduction in tailplane size. Applying a linear thrust variation over all motors, Hepperle shows that the drag created by a yawing moment is close to zero. This is more efficient than using a rudder deflection. [3.28]

The combination of both, the reduced wing area and vertical tail size as well as the wingtip mounted propellers, lead to the increase in aerodynamic efficiency shown within the radar chart in Figure 3.6.

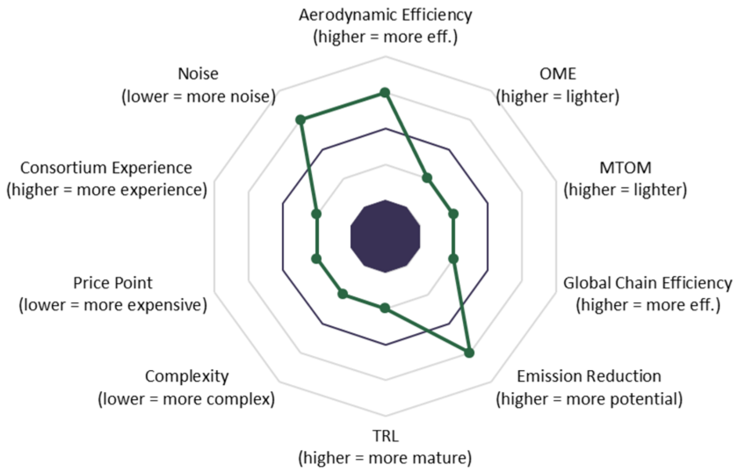

Figure 3.6: Radar Chart Guesstimate DEP Cruise Configuration

By the number of motors, not only the overall mass but also the global power train efficiency due to additional power cables will be affected negatively. Still emission reductions seem possible. The added motors will also need more electrical components which increase complexity and cost of the aircraft.

3.3.2 High-Lift Configuration

This design is quite similar to the cruise configuration with the difference that the inner propellers are optimized for high-lift and slow flight. To achieve as much additional lift as possible these propellers should produce near-uniform velocity profiles [3.26]. At normal cruise, the high-lift propellers are shut down and folded away for drag reduction. The required lift at take-off and landing will be produced by the high-lift propellers. This allows sizing the wing for cruise. In addition, if designed accordingly, the complex high-lift system containing flaps and/or slats can be replaced. In case of OEI, the high-lift propellers must be capable to generating enough thrust to fulfil certification requirements. Otherwise, additional propulsors have to be installed.

Figure 3.7: DEP High-Lift Configuration [USTUTT]

The aerodynamic efficiency of this configuration is expected to be the best of all investigated design options at the cost of added complexity by the foldable propellers (compare Figure 3.8). Also, the slim high aspect ratio wing needs further strengthening which increases the mass of the aircraft in combination with the number of motors and required power cables.

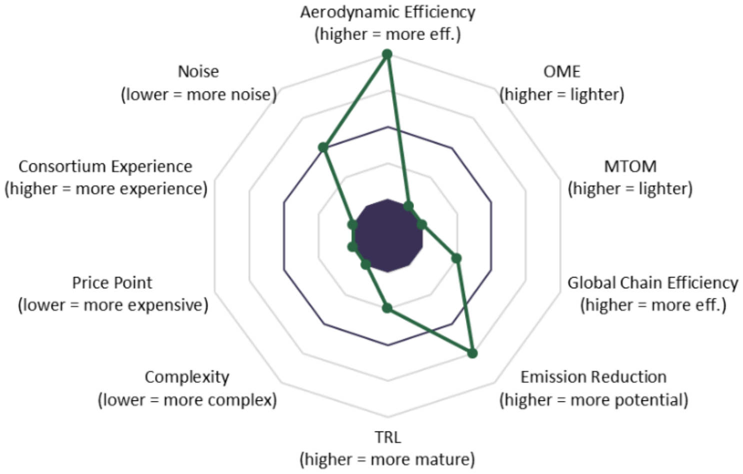

Figure 3.8: Radar Chart Guesstimate DEP High-Lift Configuration

Depending on the solver, a maximum lift coefficient of more than 4 can be achieved by the high-lift configuration of the X-57 Maxwell. From the base value 2.6 with deflected flaps, this results in a delta of more than 1.4 generated by the high-lift propulsors [3.26]. The drag reduction in cruise was estimated to 2–18 %, as already stated in the WTP chapter, with same wing planforms. Further savings are expected if comparing a “conventional” wing with the cruise optimized wing, characterized by a reduced wing area and high aspect ratio.

3.4 Hydrogen Aircraft

Hydrogen offers about three times higher specific energy than conventional jet fuel, but at the same time has a low density [3.30]. In liquid state, the required volume to store the same amount of energy is four times higher [3.30]. This volume increase enlarges the wetted area of the airplane and results in additional drag. On the other side, drag is a function of required lift and thus aircraft weight. The reduction in fuel mass leads to a decrease in required lift and with that, less drag is generated. Overall, a 20–25 % increase in OME and 8–15 % in specific fuel consumption is estimated with a reduction of 15 % in MTOM [3.30].

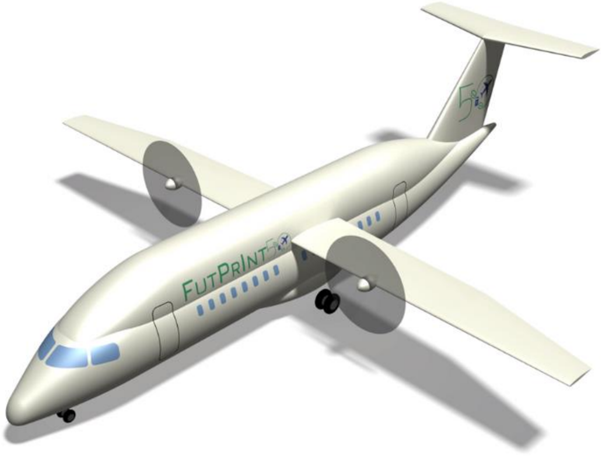

Figure 3.9: Hydrogen Aircraft [USTUTT]

The regional hydrogen aircraft concept shown in Figure 3.9 stores hydrogen in cylindrical tanks on top of the cabin. This “bubble” is partially shadowing the vertical tail. To achieve similar stability, the size of the vertical tailplane has to be increased. Other ideas include storing the hydrogen in the rear of the fuselage, by which the overall fuselage will be elongated, or adding pods under the wings as hydrogen tanks [3.30].

Furthermore, many synergies can be achieved by hydrogen aircraft. The low temperature of cryogenic hydrogen opens possibilities for superconductivity within electrical systems and wiring. Also, the low temperature of either gaseous or liquid hydrogen can be used for the thermal management of subsystems.

Probably the highest benefit is expected for emissions (compare Figure 3.10). Burning hydrogen will only leave nitrogen oxides and water as products, using fuel cells will reduce the emissions even further to only water. Care has to be taken because water is also influencing climate by contrails and aviation induced clouds. For the regional aircraft designed in FutPrInt50 this is negligible because contrails are formed in an altitude between 8–13 km [3.31], which is higher than the defined maximum altitude within the TLARs. Furthermore, Marquart et. al. state that the influence on climate of additional water emissions from cryoplanes is outweighed by the decrease in optical depth of contrails formed by these planes [3.32].

Open questions are the production of green hydrogen, storage in general as well as transport and airport infrastructure. Also, problems with boil-off losses must be faced on aircraft level.

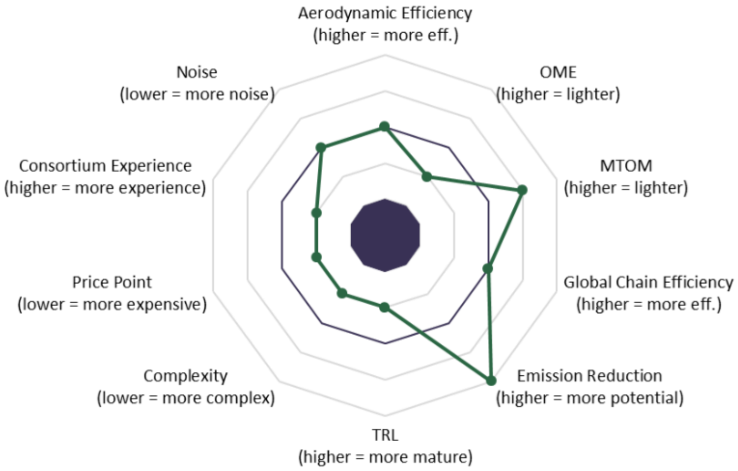

Figure 3.10: Radar Chart Guesstimate Hydrogen Aircraft

3.5 Propulsors

Within the state-of-the-art analysis of FUTPRINT50, different propulsors were investigated. Namely, propellers, ducted fans, turbofans and the open rotor fan. In the following chapters, each technology is described and the advantages and disadvantages are listed with respect to the application within a regional HEA.

3.5.1 Propeller

A propeller uses shaft power provided by a piston, turboprop or electrical engine and converts it to thrust power [3.33]. The shaft power, and with that the thrust power, remains the same with increasing airspeed. Because the thrust power is thrust multiplied by airspeed, the thrust produced will eventually decrease [3.33]. Propellers offer high efficiencies at medium speeds [33, 34] combined with good take-off performance compared to turbofans and the capability to use short and unpaved runways. A significant efficiency drop at higher speeds and altitudes is the main downside of this proven technology [3.34]. Looking at the regional HEA and the TLARs defined in FUTPRINT50, this is negligible.

3.5.2 Ducted Fan

A ducted fan is a propeller with a duct around it. In comparison to the standard propeller, the ducted fan with identical diameter produces more static thrust [3.33]. The ducted fan is quieter [3.33] by the shielding provided through the shroud which also offers limited capabilities of thrust vectoring. The duct not only increases safety on ground [3.33] but also in flight, as it can contain parts of the blade in case of failure. One drawback is the reduced efficiency in cruise conditions. Furthermore, the ducted fan is vulnerable to vibrations as a small clearance between duct and blade tips [3.33] is required to achieve high efficiencies. Additionally, parts of the duct might stall at high AoAs which increases drag and lowers thrust as well as efficiency. Overall, the duct not only adds further complexity but also mass to the aircraft. In most cases this would lead to smaller diameters than propellers and the efficiency advantages are outweighed [3.33].

3.5.3 Turbofan

The turbofan is a proven technology that is used in many different aircraft types with various mission purposes. It offers high cruise altitudes as well as high cruise speeds. The efficiency is

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lower compared to the turboprop [3.33] but for longer flights this disadvantage is equalized by the improved speed. Because of the short flight times and lower speed of the regional HEA defined within the TLARs, the advantages of the turbofan cannot be utilized. Also, required runway length would be increased.

3.5.4 Open Rotor Fan

"The […] open rotor has propellers that look and act more like the fan rotors at the front of a turbofan engine." According to Raymer an improvement of 10–30% in fuel consumption is possible at the cost of increased noise. This is achieved by the extreme blade diameter. [3.33]

This will require a higher mounting position for the engine which might cause stability issues in thrust variations especially in case of a go-around manoeuvre.

Rossow et. al. state an improvement of around 20% compared to a conventional turbofan engine. To counter the increase in noise one suggestion is to cover the open rotor fan with parts of the wing or horizontal/vertical tail. [3.34]

Safran has achieved TRL 5 for the Open Rotor after a test campaign in 2017 [3.35], so this is the least mature technology investigated. Furthermore, Safran is confident after a wind tunnel test performed in 2013 that the noise emissions are similar to the LEAP turbofan [3.36].

3.6 Structural Battery

The structural battery aims at producing multifunctional structure or material. According to Adam et. al., it can be split into four levels plus the classical approach. The following principle applies: "Towards higher degrees of structural integration, the energy-storing capability is gradually transferred to the composite laminate." [3.37]

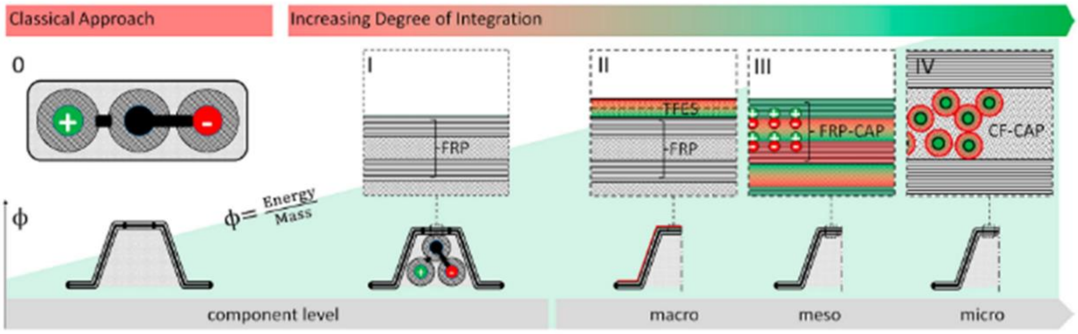

Figure 3.11: Integration Level of Structural Batteries [3.37]

In the classical approach (Level 0) the load bearing structure and batteries are separated from each other. Both parts are especially built for only one purpose which allows easy integration and accessibility. [3.37]

By Integrated Non-Load Carrying Cells (Level 1) the cells are placed into the volume within unused spaces of structural components. The total savings are not significant because the cells are already optimized for mass savings. [3.37]

Integrated Thin-Film Energy Storages (TFES, Level 2) represent a macro level. Here, the energy storage is integrated within the laminate as a separate layer. By this, the housing is replaced by the load carrying laminate itself. Mass as well as volume savings are possible. However, the different mechanical properties of the separate layers can cause problems and in the worst-case delamination. [3.37]

The Structural Laminate Energy Storage (Level 3 – meso level) is described as the first multifunctional material approach in which the laminate fulfils two separate functions: Carrying load on the one hand as well as storing energy on the other. It consists of carbon layers as electrode, glass layers as separator and an ion conducting matrix. The matrix is the most ambitious task, as increasing ion conductivity will decrease stiffness of the material and vice versa. [3.37]

The aim of the fourth level (Microscaled Coaxial Fibre Energy Storage, Micro Level) is to eliminate the separation layer. For example, this can be achieved by using an inner fibre as first electrode and a hollow outer electrode with same material properties. Both are separated by a porous, electrically isolating layer. Again, "electrically contacting is an issue to be solved." [3.37]

For a full-electric two-seater aircraft Scholz calculates, that a specific energy of 51.8 Wh/kg and a specific power of 103.3 W/kg is needed to achieve a comparable mission performance to a conventional aircraft. To achieve this a five times higher overall specific energy is required than today. However, increasing energy storage capabilities is contradictory to high mechanical properties [38]. All in all, the combination of load bearing structure and energy storage offers mass reduction possibilities as well as a reduced number of power cables if consumers can be connected close to their location. [3.39]

Another open question is the replacement of malfunctioning cells in combination with the aircraft life cycle and thus the ability to use primary structure as multifunctional material.

All in all, the technology is expected to be not mature enough until the projected EIS of the FutPrInt50 regional HEA in 2035/2040.

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4 Energy Storage

4.1 Conventional lithium-ion batteries, supercap and LiC

Lithium-ion batteries currently dominate the battery market for portable electronic devices (laptop, cell phones) and electric vehicles. They have a high energy density and cyclability compared to other battery technologies. At cell level, energy density for current high-energy cells reaches 250 Wh/kg and max power density in discharge for power cell is around 3 000 W/kg. Many chemistries exist. For the positive cathode, main materials are NMC (lithium nickel manganese oxide), NCA (lithium nickel cobalt aluminium oxide), LMO (lithium manganese oxide), LCO (lithium cobalt oxide), LFP (lithium iron phosphate), or some blend. For the negative anode, we can find C (graphite, sometimes blend with silicon oxides or silicon nano-particles) or LTO (lithium titanate oxide). The final performance of the cell is a compromise between energy, power, safety, durability and cost. It results from the chemistry but also from the cell's design and manufacturing process (shape, structure, quality, internal protections).

Besides batteries, **supercapacitors** (also called 'EDLC' for 'Electric Double Layer Capacitor') have the advantage to be able to deliver high peak current during short time (~ 15 000 W/kg). Moreover their cyclability and calendar life are very important (~1 000 000 cycle at 50% depth of discharge, 20 years). Nevertheless, their energy is far lower than lithium batteries. **Lithium-ion Capacitor** ('LiC') are hybrid components between lithium-ion battery and supercap, with intermediate performances. For some applications, supercap or LiC can be associated to battery in order to optimize the global system's size or lifetime.

4.2 Future battery technologies

Solid-state batteries at ambient temperature are not mature for commercialization yet, but are very promising for the future. They substitute the liquid electrolyte with a solid polymer or a ceramic separator, and therefore could improve **safety**. Moreover, they can be combined with pure lithium metal negative electrode (**lithium-metal battery**), which is not safe enough otherwise because of dendrites growth. Indeed, lithium-metal battery could increase **energy density** up to 530 Wh/kg (at cell level). Research studies on solid-state batteries generally focus at the solid electrolyte material, conductivity, stability, interfaces, and battery processability. The potential gain for safety must also be investigated more deeply since, even without internal short-circuit, some other phenomena such as O_2 release may occur and lead to thermal runaway.

Lithium-sulfur batteries also represent a very interesting prospective technology. They are made of a lithium-metal anode and a sulfur based cathode. Sulfur is very lightweight. Consequently, the specific **energy density** of these batteries is high (550 Wh/kg at cell level). With regard to materials, lithium-sulfur battery utilizes sulfur, which is abundant and cheap, instead of heavy metal such as the critical cobalt. Some companies, like OXIS Energy or SION Power, already commercialize cells. However, for the moment their lifespan and energy are still low.

Lithium-air (O_2) batteries are at exploratory stage only. They are often presented as as an ultimate future battery for energy density. Nevertheless, even if its **theoretical** specific energy is significant, we need several extra components to purify oxygen from air or to enclose the system. As a result, when we consider the whole system, projections show that we obtain **comparable** cost, volume, and mass to other advanced chemistries that are in more mature states of development and have less technical risks.

Many other technologies are also in research phase but not described in this report. We only choose to report those that are being seriously studied and that seem to be the most adapted to a hybrid-electric application. For instance, Na-ion has low energy density and is not considered here.

	Current Li-Ion	**Optimistic Li-Ion***	**Optimistic Li-Sulfur***	**Optimistic Li-Air***
Specific Energy Density – Wh (total)/kg (cell)	250	530	550	710
Specific Energy Density – Wh (total)/kg (system)	150	290	300	280
Energy Density – Wh (total)/liter (cell)	520	1050	620	760
Energy Density – Wh (total)/liter (system)	230	375	260	240

**Assumes Li-metal negative*

Table 4.1: Specific energy density for current and future lithium-ion technologies [4.1]

Figure 4.1 compiles several roadmaps for battery energy density. They have been established by different famous battery manufacturers or by consortiums for battery research in China, USA, Japan or Europe. If we extrapolate it to 2035-2040, we can suppose that the cell's energy density should be close to approximately **600 Wh/kg**. Note that there are many uncertainties for this kind of projection. For instance, Figure 4.1: Roadmaps for battery energy density [4.2] is related to the energy density and does not detail the other performances such as power and safety.

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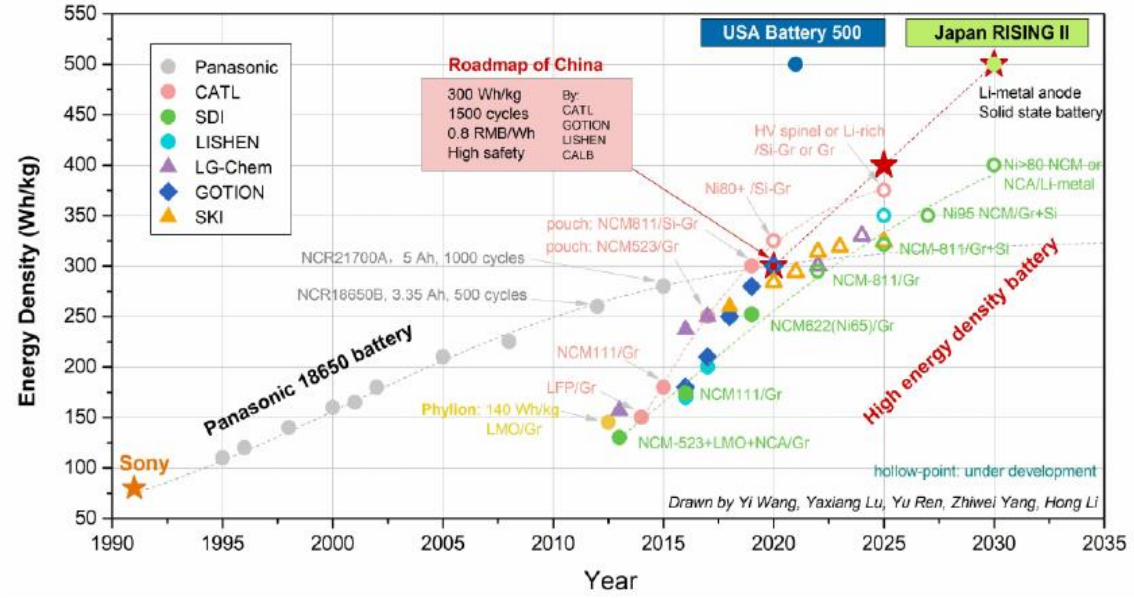


Figure 4.1: Roadmaps for battery energy density [4.2]

4.3 Battery safety

Battery safety is one of the main challenges, especially (but not only) for aeronautics. Accidents (ex: Boeing Dreamliner) may have dramatic effects. Of course, human lives can be involved. In addition, even if people are not injured, there can be huge economic impacts. All battery manufacturers and laboratories are being working intensively to improve battery safety, taking into account that the energy density is also increasing progressively year by year.

Among the different risks, the cell’s thermal runaway, as well as the risk to propagate it to the other cells, belong to the items that must be secured to obtain a safe system. For instance, we must manage the potential cell’s gases and projections during the thermal runaway. The RTCA DO-311A standard describes requirements and tests for battery safety in aeronautics.

4.4 Battery system and integration

We often simplify battery to one battery cell. Nevertheless, the **battery pack complete system** is made of many cells and other components. For instance, the battery pack of the Tesla S 75D electric vehicle, which is 72 kWh, contains more than 6000 small cylindrical cells, a water-glycol cooling, electronics control units, and other electric devices.

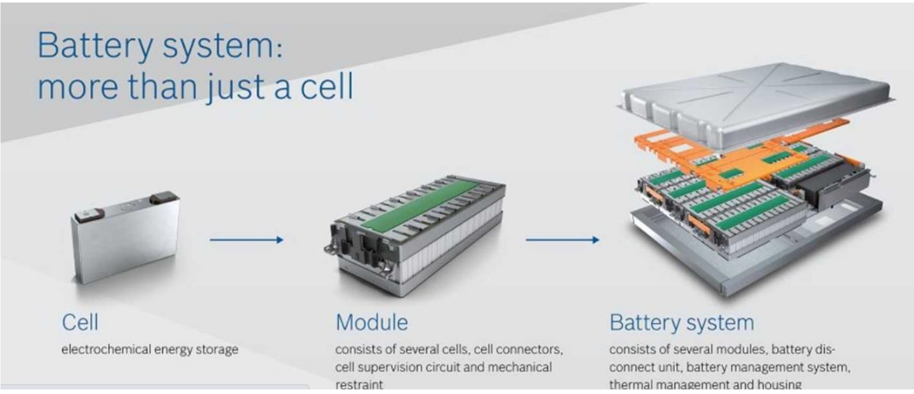


Figure 4.2: Battery system [4.3]

For the hybrid-electric airplane, the pack system global design must be defined for **mechanical, electrical and thermal integration** in the airplane, considering **safety** constraints. The ratio between the cells' weight and the complete battery pack weight is approximately 55 to 78 % for existing automotive systems. For 2040, we can expect to have this ratio around approximately 75 % for aeronautics. Indeed, we should have integration improvements for the battery mechanical parts, especially for the housing. The use of **composite** materials and **additive manufacturing** will help to reduce the mass and in the same time to integrate more functions within less components. The split of the standard large battery pack into smaller integrated and distributed batteries is also a possibility. Structural batteries must be explored, even if, for the moment, their TRL is very low. On the other hand, safety requirements will request robust mechanics and integration and will affect the ratio.

New **electrical architectures** using electronic devices will also give safer battery systems.

For battery **thermal management**, several technologies are possible: air or liquid, indirect or direct. The technology selection depends on many criteria: integration to the global aircraft thermal management system, battery mission profile and heat to be drained out, etc. If a high efficiency cooling system is required, note that direct cooling (immersed battery) is already used in some datacentres or power electronics applications.

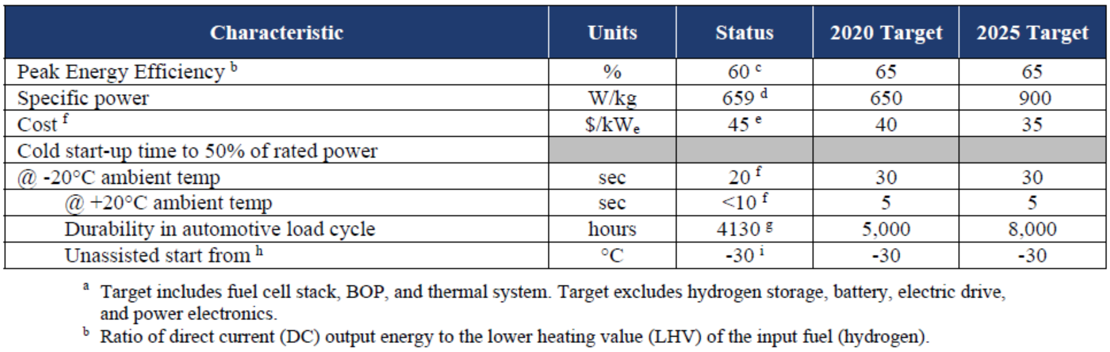
4.5 Fuel Cell

A fuel cell (FC) is an electrochemical generator that converts the chemical energy of a fuel (e.g. hydrogen, methane, methanol…) and an oxidizing agent (e.g. oxygen) into electricity and heat. In the common case of hydrogen and oxygen, the products of the redox reaction are water (liquid and/or vapour), electricity and heat. A fuel cell stack is a stack of elementary fuel cells electrically connected in a series, thus enabling to reach higher power and higher voltage than a single cell. In addition, auxiliaries components (also called balance of plant – BOP) are required to operate the fuel cell stack: fuel tank, fuel lines, air mover (e.g. compressor), air ducts, water management system, cooling system, sensors, monitoring and control unit…

There are many fuel cell technologies including but not limited to Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten-Carbonate Fuel Cell (MCFC), Proton-Exchange

Membrane Fuel Cell (PEMFC) and Solid Oxide Fuel Cell (SOFC). The fuel cell technologies considered today for aeronautics are mainly PEMFC and SOFC. SOFC operate between 550°C and 1000°C, use a non-precious catalyst, and can be fed with hydrogen or hydrocarbons, directly at anode inlet or with an additional reformer. PEMFC use a precious catalyst (platinum) and split into three categories corresponding to three ranges of operating stack temperature: high temperature (HT-PEMFC, 120 °C to 180 °C), medium temperature (MT-PEMFC, 90 °C to 120 °C) and low temperature (LT-PEMFC, 60°C to 80°C). The higher the stack temperature, the smaller the size & weight of the required cooling system and the easier energy that can be generated from heat. Nevertheless, LT-PEMFC is the most considered option today for aeronautics and automotive thanks to its higher maturity (TRL9 in automotive) and its higher specific power.

Table 4.2: Technical targets for automotive-scale (80 kWe net) fuel cell system operating on hydrogen [4.4] shows the 2017 roadmap for automotive Fuel Cell Systems. Specific power for LT-PEMFC systems is currently 650 W/kg and is expected to be 900 W/kg in 2025, including BOP.



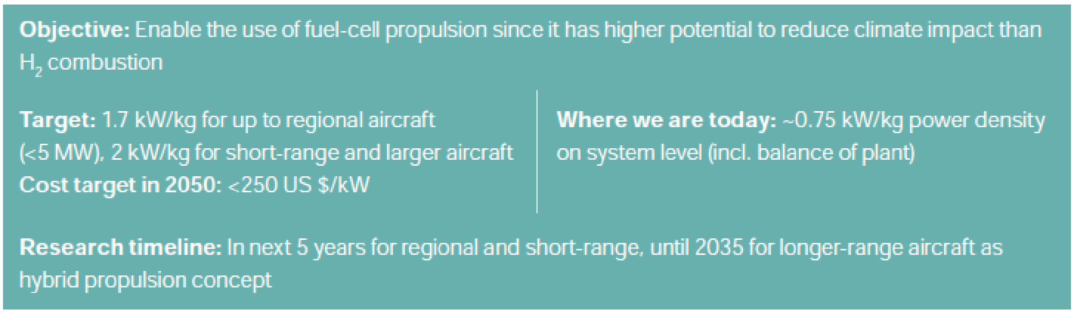
Characteristic	Units	Status	2020 Target	2025 Target
Peak Energy Efficiency [b]	%	60 [c]	65	65
Specific power	W/kg	659 [d]	650	900
Cost [f]	$/kW$_e$	45 [e]	40	35
Cold start-up time to 50% of rated power				
@ -20°C ambient temp	sec	20 [f]	30	30
@ +20°C ambient temp	sec	<10 [f]	5	5
Durability in automotive load cycle	hours	4130 [g]	5,000	8,000
Unassisted start from [h]	°C	-30 [i]	-30	-30

[a] Target includes fuel cell stack, BOP, and thermal system. Target excludes hydrogen storage, battery, electric drive, and power electronics.

[b] Ratio of direct current (DC) output energy to the lower heating value (LHV) of the input fuel (hydrogen).

Table 4.2: Technical targets for automotive-scale (80 kWe net) fuel cell system operating on hydrogen [4.4]

Figure 4.3 shows the 2020 roadmap of a study dedicated to hydrogen-powered aviation [4.5] for aeronautics Fuel Cell Systems. Specific power for LT-PEMFC systems is currently 750 W/kg and is expected to be 1700 W/kg in 2025 for fuel cell power up to 5 MW including BOP. These values are considered by the experts of the study [4.5] as ambitious but achievable in 2025-2030.



Objective: Enable the use of fuel-cell propulsion since it has higher potential to reduce climate impact than H_2 combustion

Target: 1.7 kW/kg for up to regional aircraft (<5 MW), 2 kW/kg for short-range and larger aircraft
Cost target in 2050: <250 US $/kW

Where we are today: ~0.75 kW/kg power density on system level (incl. balance of plant)

Research timeline: In next 5 years for regional and short-range, until 2035 for longer-range aircraft as hybrid propulsion concept

Figure 4.3: Status and targets for aeronautics fuel cell system from [4.5]

4.6 Hydrogen Storage

Hydrogen (H_2) is the fuel with the highest energy gravimetric density (Low Heating Value = 120 MJ/kg), but it requires more volume than other fuels (Figure 4.4).

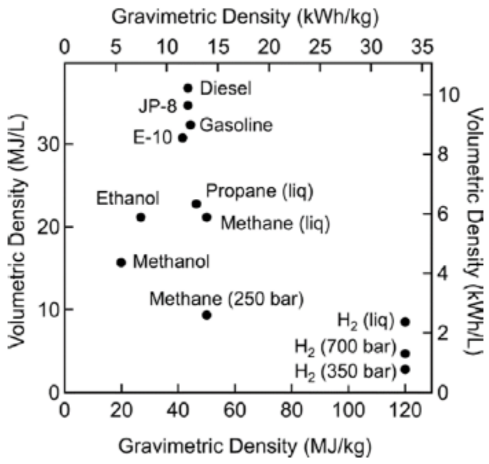
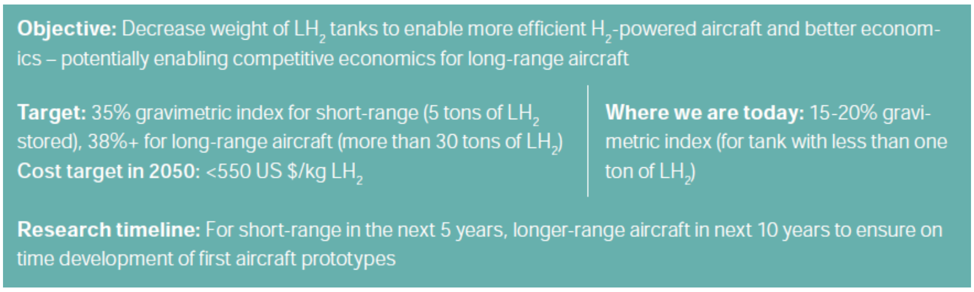


Figure 4.4: Comparison of the volumetric and gravimetric densities of various fuels (without tank; energy refers to Low Heating Value) [4.6]

There are many hydrogen storage technologies (physical-based: Compressed Gaseous Hydrogen CGH2 at ambient temperature, cryo-compressed or liquid hydrogen LH2; or material-based: metal hydrides like $NaAlH_4$, adsorbents, etc.) with different TRL, features and ease of use. The most common hydrogen storage technology for on-road applications (automotive, buses…) is CGH2 (typically 350 bar or 700 bar). State of the art gravimetric index (weight of hydrogen / weight of tank full with hydrogen) of CGH2 is around 4.5 % wt and is expected to reach 6.5% wt as ultimate target in the US automotive roadmap [4.6]. The storage technology offering the highest gravimetric index is LH2, with currently 15-20 % wt and an expected 35-38 % wt in 2025-2030 [4.5] (Figure 4.5). These values are considered by the experts of the study [4.5] as ambitious but achievable in 2025-2030.

To be liquid, hydrogen has to be cooled down to 20 K. A relief valve let gaseous hydrogen escape from the LH2 tank in order to keep the tank pressure at a low level (typically a few bars). This hydrogen "boil-off" is due to the heat flowing into the tank despite its thermal insulation. The thermal insulation of the LH2 tank should be sized in order to find a trade-off between the weight of the thermal insulation and boil-off losses happening when the fuel cell does not consume hydrogen.



Objective: Decrease weight of LH_2 tanks to enable more efficient H_2-powered aircraft and better economics – potentially enabling competitive economics for long-range aircraft

Target: 35% gravimetric index for short-range (5 tons of LH_2 stored), 38%+ for long-range aircraft (more than 30 tons of LH_2)
Cost target in 2050: <550 US $/kg LH_2

Where we are today: 15-20% gravimetric index (for tank with less than one ton of LH_2)

Research timeline: For short-range in the next 5 years, longer-range aircraft in next 10 years to ensure on time development of first aircraft prototypes

Figure 4.5: Status and targets for aeronautics LH2 tanks from [4.5]

4.7 Weight of Fuel Cell and Hydrogen Storage systems for FutPrInt50aircraft

Weight of H2 tank increases with the electrical energy to be provided. Weight of fuel cell system increases with the maximum electric power to be provided. Overall weight of a PEMFC system and its H2 storage system (including balance of plant and excluding hybrid battery and power electronics) has been calculated with some preliminary data for FutPrInt50 project. An equivalent net energy density of the whole system (PEMFC + H2 storage) was also calculated based on these assumptions (Table 4.3).

As a result, installing a fuel cell system and a hydrogen storage system based on current automotive technology would result in a net energy density of ca. 350 Wh/kg (including balance of plant, excluding power electronics and hybrid battery) for a typical FutPrInt50 mission. Considering the 2025 targets for aeronautics fuel cell systems and LH2 storage system for a regional/short range aircraft, the net energy density would be around 1300 Wh/kg. Hybridization of the FC system with a battery might be relevant to reduce the max power of the FC and thus the size and weight of the fuel cell system.

Case (PEMFC system specific power and hydrogen storage system gravimetric index)	Overall Weight	Overall net energy density
State of the art automotive (650 W/kg, CGH2 4,5%wt)	2297 kg	348 Wh net/kg sys
State of the art aeronautics (750 W/kg, LH2 20%wt)	1307 kg	612 Wh net/kg sys
Target 2025 aeronautics (1700 W/kg, LH2 35%wt)	608 kg	1316 Wh net/kg sys

Table 4.3: Weight and equivalent net energy density of a PEMFC system and its Hydrogen storage system.

4.8 Fuel Cell and Hydrogen Storage safety and integration in aircraft

Hydrogen can be used with different energy conversion technologies: turbojet engines, internal combustion engines, turbine coupled with an electric generator and electric motors, Solid Oxid Fuel Cells, PEM Fuel Cells… Hydrogen was already used successfully in multiple test flights (Tupolev TU-155 in 1988 [4.7], Airbus A320-232 ATRA in 2008, HY4 aircraft…).

The volume of LH2 tanks is approximately 4 times higher than that of kerosene tanks [4.5]. Different locations can be considered for these bigger tanks [4.7] (Figure 4.6).

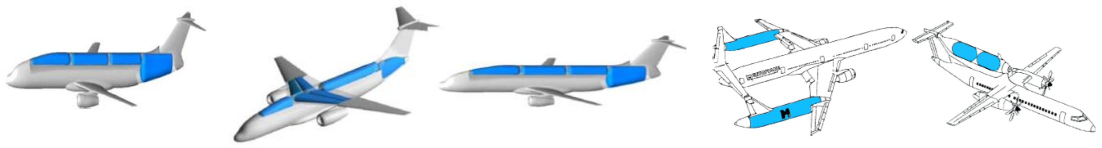


Figure 4.6: Hydrogen aircraft with different configurations of hydrogen tank (in blue) [4.7].

Unlike batteries that both store energy and deliver electric power, the energy storage and the energy conversion of a fuel cell power system occur within two different subsystems: the fuel tank and the fuel cell respectively. This separation can be an advantage in terms of safety compared to batteries because it is possible to isolate the hydrogen tank if needed. In case of fire, TPRD (Thermally Activated Pressure Relief Device) are used to prevent rupture of the hydrogen tank: the hydrogen will be released in a controlled manner through a venting system. In comparison to a kerosene aircraft, the hydrogen aircraft would remain almost intact in that case (Figure 4.7).

Figure 4.7: Comparison of hydrogen and kerosene fire done by the University of Miami (picture from [4.7])

Many synergies between hybrid aircrafts and hydrogen fuel cell systems might be considered. Electricity might be used for taxi, on board equipment, main engine starter. Heat might be used for de-icing, hot water, galleys. Water might be used for cabin air humidification, as water to drink or for the toilets. Oxygen depleted air might be used to intert kerosene tanks. Cold from LH2 tanks might be used for cooling, improving reliability and lowering weight of electrics and electronics. Several large projects for hydrogen aircrafts have been launched. Again very recently, Airbus has announced its program of hydrogen 'ZEROe' airplanes from 2035.

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A more detailed set of references can be found in Appendix A4

5 Hybrid-Electric Prime Movers and Electric Motors

5.1 State of art of hybrid/electric propulsion systems

Hybrid-electric, turboelectric and all electric propulsion systems are promising way to reduce emission. The idea of electrifying the propulsion systems is divided into:

1. All electric;
2. Turboelectric;
3. Hybrid electric.

The architectures are characterized as per the extent of usage of the electrical energy source and based on the electrical propulsion system arrangement.

5.1.1 Degree of hybridization

Hybrid electric propulsion system can be described by two parameters. The first one is Degree of Power Hybridization (or Degree of Hybridization), the second is Degree of Energy Hybridization (or Degree of Electrification). These parameters help to classify propulsion systems.

Degree of Power Hybridization is ratio of electric motor shaft power to the total motor shaft power. This parameter shows how much electric power propulsion system use.

$$H_P = \frac{P_{Elec,Shaft,Tot}}{P_{Elec,Shaft,Tot} + P_{GT,Shaft,Tot}}$$

Degree of Energy Hybridization is ratio of electric energy from batteries of fuel cell to the total energy. This parameter shows how electric-chemical sources are involved.

$$H_E = \frac{E_{Elec}}{E_{Elec} + E_{Fuel}}$$

According to this parameters, we can conclude that the parallel and partial serial hybrid-electric topologies offer the highest degrees of freedom for the design exploration (Table 5.1).

Type of propulsion system	Degree of Power Hybridization	Degree of Energy Hybridization
Conventional	0	0
Partial Turboelectric	0 ÷ 1	0
Turboelectric	1	0
Serial Hybrid	1	0 ÷ 1
Parallel hybrid	0 ÷ 1	0 ÷ 1
Partial serial Hybrid	0 ÷ 1	0 ÷ 1
All electric	1	1

Table 5.1: Parameter range for the different (hybrid) electric topologies

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5.1.2 All electric configuration

All electric system relies upon galvanic cells (battery, fuel cells etc.) or some other means of electrical energy storage. Such design features the advantages of a highly efficient conversion system and is the only configuration which has the potential for zero inflight emission and is much quieter in operation.

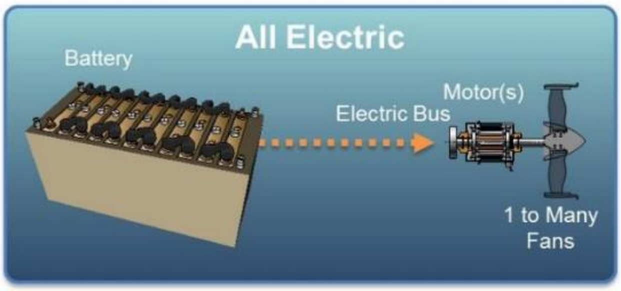


Figure 5.1: All electric configuration

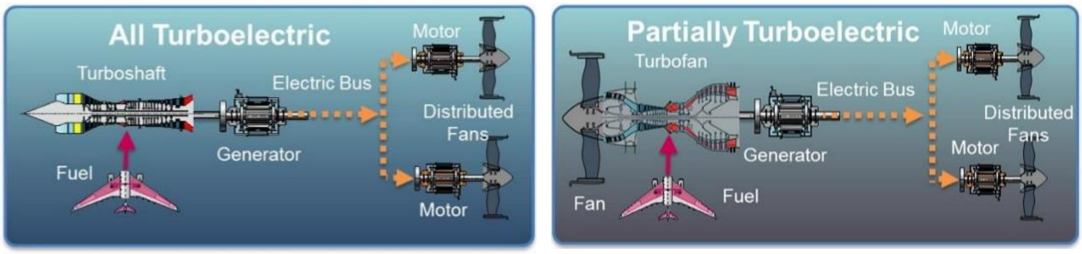
Today, there are some projects with the full electric propulsion system. For example, NASA's SCEPTOR X-57 [5.1] and Ce-Liner [5.2] designs in the regional and single aisle segments, respectively. The most parts of the aircrafts in this category are designed for smaller size, with a few exceptions.


a) *b)*

Figure 5.2: All electric aircrafts. a – X-57 Sceptor, b – Ce-Liner

5.1.3 Turboelectric configuration

Turboelectric propulsion system use fuel as main source of energy and converts the chemical energy available in the fuel into electrical power either fully or partially to drive the propulsor. Distinguish the partially turboelectric propulsion system where the propulsive thrust is produced by both gas generator driven propulsors and the turbofans.



a) *b)*

Figure 5.3: Turboelectric configuration. a – all turboelectric, b – partially turboelectric

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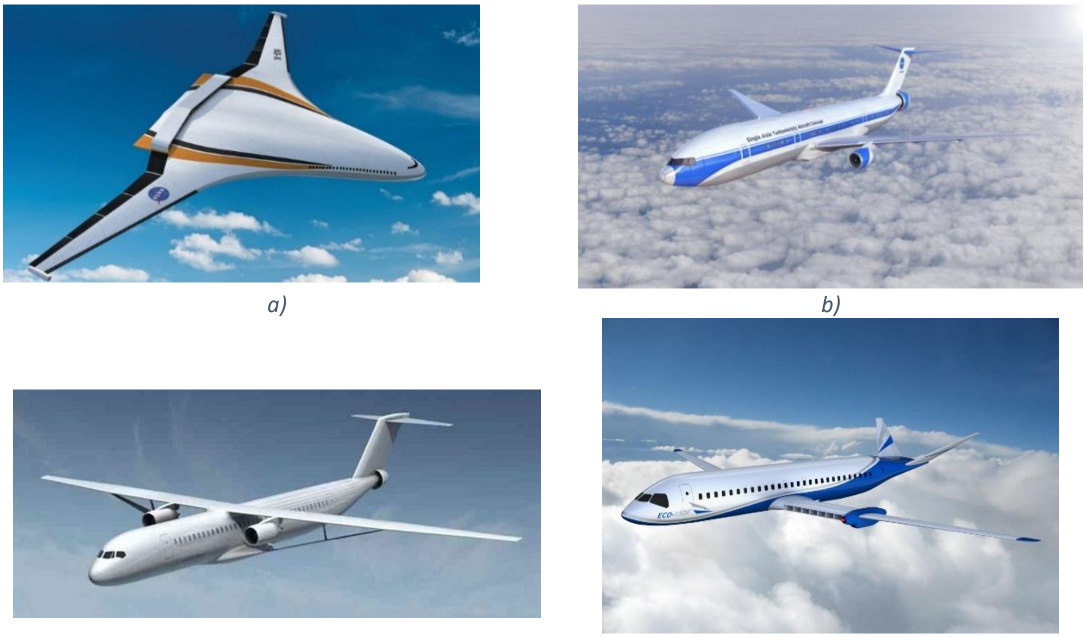
A turboelectric configuration have profits because of size of one turboshaft engine. One powerful engines has better specific parameters than two low power. Moreover, turboelectric propulsion is well suitable for the innovative concepts of aircraft such as distributed propulsion arrangement with or without a boundary layer ingesting system.


a) b)

c) d)

Figure 5.4: Turboelectric aircrafts. a – NASA N3-X, b – STARC-ABL, c – Boeing Sugar Freeze, d – ECO-150

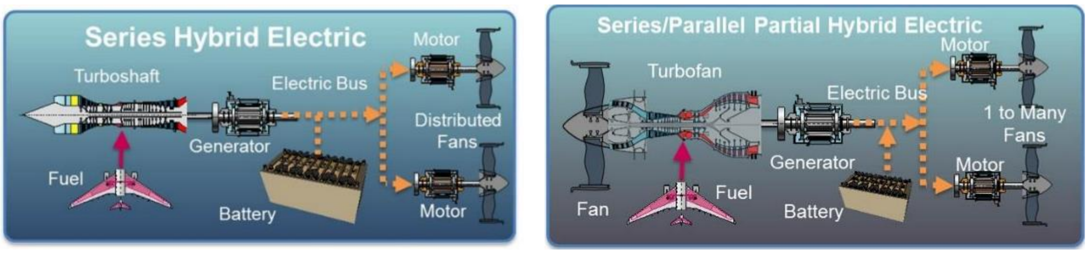
It is established that successful application of the aircraft based on turboelectric/partially turboelectric configurations has a high reliance on superiority of the electrical drivetrain components' technologies [5.3–5.5]. The system level benefits and challenges of fully/partially turboelectric configurations were studied under NASA's N3-X [5.6–5.8], the single-aisle partially turboelectric aircraft with an aft boundary layer propulsor (STARC-ABL) design [5.9, 5.10], Boeing's Subsonic Ultra Green Aircraft Research (SUGAR) Freeze design [5.11], and Empirical Systems Aerospace Inc. (ESAero)'s Environmentally Conscious 150 (ECO-150) design [5.12].

5.1.4 Hybrid electric architectures

The term hybrid electric is coined for the options wherein the propulsion system utilizes more than one type of energy sources, such as fuel/chemical and battery/electrochemical system. All hybrid electric architectures divided into series, parallel and series/ parallel propulsion systems, which are based on the nature of the node connecting the two constituent energy sources.

5.1.4.1 Serial hybrid architecture

In a serial hybrid propulsion system, the propulsors are supplied electrically from a gas turbine driven generator and from galvanic cells (battery, fuel cells and etc.) or some other means of electrical energy storage. This topology enables decoupling of the gas turbine system from the propulsors by an electrical conversion and the transmission system. One of the benefits of this topology is the flexibility to operate the gas turbine engine independent of the fan speed, thus it makes possible to operate at its maximum efficiency.



a) *b)*

Figure 5.5: Serial hybrid configuration, a-full, b-partial

Also, serial hybrid propulsion system provides energy to take-off from batteries or fuel cell, and it gives an opportunity for sizing the Gas Turbine Engine for a lower thrust requirement condition. There are two types of serial hybrid propulsion system: full or partial. In case of partial series propulsion system part of energy of turbofan use to drive propulsor directly.

Aircraft of startup Zunum Aero with Serial hybrid propulsion system have 1 MW of maximum power. The main goal of the project is 50 passenger capacity aircraft. But there are versions with smaller capacity. Maximum payload of 12-seating version is 1100 kg, it has 1100 km range and 550 kmph cruise speed [5.13].

Figure 5.6: Zunum Aero

5.1.4.2 Parallel hybrid architecture

In a parallel hybrid configuration, both the electrical motor and gas turbine engine are connected mechanically to drive the propulsor. This topology offers high flexibility in combination of different components of the total propulsion system. Since there is no electric generator in this topology, this leads to weight saving.

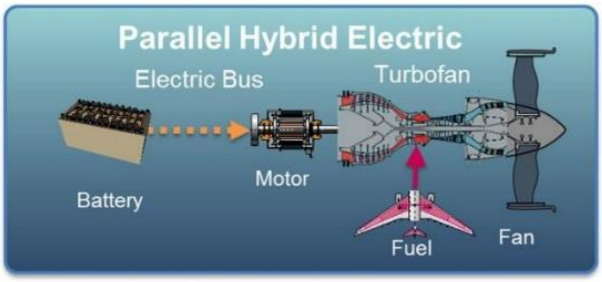


Figure 5.7: Parallel hybrid configuration

As well as serial topology, the parallel hybrid electric propulsion system can use electric power for boosting the engine during the peak flight modes [5.14, 5.15] and/or to charge the battery under low thrust requirement conditions [5.16]. Thus, it gives an opportunity for sizing the Gas Turbine Engine for a lower thrust requirement condition and leads to increasing their fuel efficiency. The advantages of this topology are widely studied in the papers [5.17, 5.18].

One of the projects that use parallel propulsion system is SUGAR Volt, developing by NASA. This aircraft have two UHB, hybrid gas-turbine/electric engines – BPR = 18, high-power-density cores – OPR = 59, with advanced combustor, low-weight high wing, advanced passive core-nozzle acoustic treatment, aggressive active noise suppression in combustor. NASA promise that SUGAR Volt will have removable batteries with possibility to add new battery, expected noise reduction is -22 EPNdB [5.19].

Figure 5.8: Boeing Sugar Volt

5.1.5 Conclusion

Although the main goal is zero-emission aircraft (all electric aircraft), it is expected that these aircrafts will not have enough range in near or mid-time frames even the optimistic way of electric components development [5.20]. By using the lower specific energy in the batteries is a limitation in the evolution high-power all electric aircrafts. Thus, hybrid electric and turboelectric propulsion systems is compromise between high range of conventional aircraft and low emission of the all-electric aircraft. Although a hybrid electric and turboelectric propulsion systems have less efficiency than all-electric architectures, but it could certainly be a step towards the development of zero-emission aircraft.

5.2 State of the art gas turbine engines for propulsion systems of regional aircraft

Currently, the main developers and manufacturers of regional aircraft in service are Bombardier (CRJ Series family with turbofan engines and Q Series family with turboprop engines, Canada), Embraer (ERJ 145 family, E-Jets family and E-Jest E2 family with the turbofan engines, Brazil) and ATR (ATR42 / 72 families with turboprop engine, Italy). ATR is a joint venture of Leonardo (50%) and Airbus Group (50%).

In the early 2000s, companies from Russia, Ukraine, China and Japan announced their desire to develop regional aircraft of various classes. If the aircraft created in Russia (SS100), Ukraine (An148 and An-140) and China (ARJ700 and MA60 / 600) are certified and entry into service in

2010-2016, then an entry into service of the Mitsubishi Heavy Industries SpaceJet (former MRJ) regional aircraft with PW1200G turbofan engine carried over to 2021 and 2022 [5.21-5.24].

As of the end of May 2019, the leading positions in the aircraft engine market segment for regional jets in service were held by General Electric (~ 71%, the CF34 turbofan engines family, T_0=35-80 kN) and Rolls-Royce (18%, AE3007 turbofan engines, T_0=35 kN) companies (Figure 5.9) [5.25].

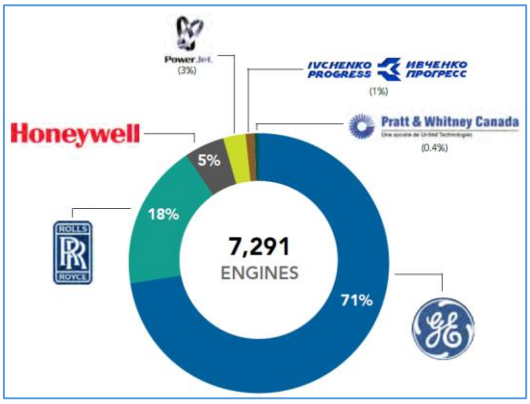


Figure 5.9: Engine market share by regional jet market group

In addition to the AE3007 turbofan engine, Rolls-Royce supplied the Tay 620/650 turbofan engine for propulsion systems of Fokker F70/ F100 regional jets, production of which were discontinued [5.26, 5.27].

The TFE731, ALF502/ ALF507 with geared fan drive and AS977 with direct drive fan of Honeywell company are used in the propulsion systems of BAE Systems BAe146/Avro RJ regional jets, production of which are discontinued.

In addition to the General Electric, Rolls-Royce and Pratt & Whitney engines, the Power Jet SaM146 turbofan engine (SJ100), D-436-148 turbofan engine and TV3-117VMA-SBM1 turboprop engine of Ivchenko-Progress company (An-148 and An-140, respectively) are used in the propulsion systems of regional jets.

For the propulsion systems of a new generation of regional jets (Embraer E-Jets E2 and MHI SpaceJet), aircraft manufacturers selected the Pratt & Whitney PW1000G turbofan engines family.

Concerning to the turboprop airplanes, Pratt & Whitney Canada PW100/150 turboprop engines family (P0=2100-5100 shp) are used in their propulsion systems.

Pratt & Whitney PW1000G turbofan engines family. Pratt & Whitney, wanting to win back a part of engine market segment for the propulsion systems of regional jets (PAX > 70) from General Electric and to return to the engine market segment of medium-haul aircraft, offered its customers the new turbofan engines family – *PW1000G with geared fan drive* [5.28, 5.29].

This family is created based on the three new gas generators of different size. Gas generator consists a *8-stage HPC, a low-emission combustor and 2-stage HPT*. The two new families –

PW800 for business jets and PW1000G for narrow-body aircraft (regional jets and medium-haul aircraft) are created based on these gas generators [5.30].

The Pratt & Whitney new engine fuel efficiency improvement program provides for the phased implementation of advanced technologies that by 2020-2022 for the PW1000G turbofan engines family should provide an additional a 8% reduction of fuel burn relatively 1st generation of engines [5.31].

Pratt & Whitney Canada PW100/150 turboprop engines family. PW100/150 turboprop engines family with take-off power P0e=1800-5100 shp have been in service for over 30 years. Engines of this family are used in propulsion systems of turboprop aircraft and on short routes (up to 500–700 km) they provide 25-40% reduction fuel burn than similar regional jets [5.32-5.35]. The development of a PW100 family on power is shown in Figure 5.10.

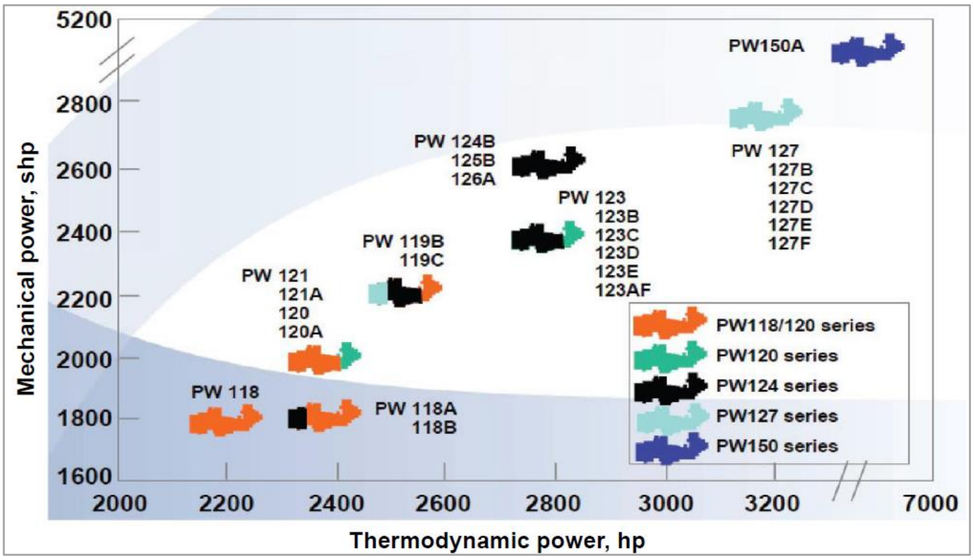


Figure 5.10: Mechanical power vs. Thermodynamic power of PW100/150 turboprop engines family

The PW100/150 turboprop engines family based on a 2-spool gas generator with an independent drive of each spool. Engine consists from (Figure 5.11):

- air intake with a protective grid;
- single-stage centrifugal (PW118 and PW127 series, PR= 4.3) or a 3-stage axial (series PW150) LPC blisk from Ti-alloy;
- single-stage centrifugal HPC (PR=4.3);
- reverse flow low emission combustor;
- single-stage gas generator turbine (TET=1420-1530 K) with an improved cooling system for vanes and blades with TBC;
- single-stage uncooled counter-rotating LPT;
- 2-stage (PW118 and PW127 series) or 3-stage (PW150 series) power turbine with shrouded blades;
- electronic control system (PW118 and PW127 series) or FADEC control system (PW150 series);
- gearbox with propeller axis offset.

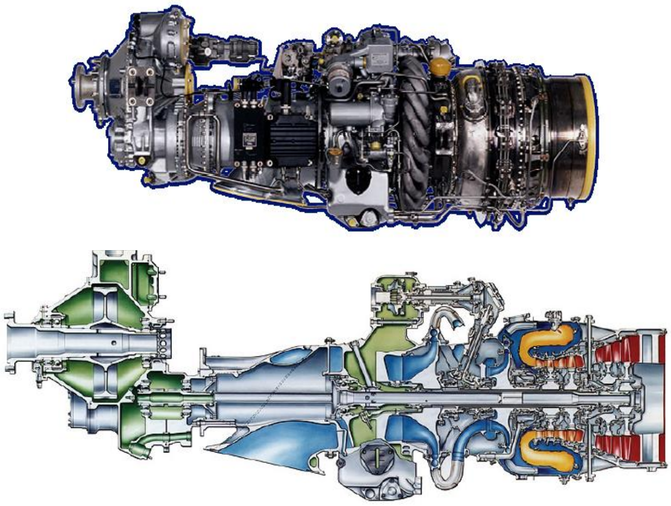


Figure 5.11: PW100/150 family turboprop engine

Currently, Pratt & Whitney Canada is working on the development of critical technologies for a new generation turboprop engine with take-off power P_{0e}=5000-7000 shp for turboprop aircraft. Similar work is being carried out by General Electric, planning to create a new turboprop engine based on the T408 (GE38-1B) turboshaft engine used in the propulsion system of the CH-53K heavy helicopter [5.36-5.38].

It should be noted, that about 85-90% module technologies are common for turboshaft and turboprop engines. If now there are no orders from turboprop aircraft developers for the new generation turboprop engines with a power P_{0e}>2000 shp, then the orders are from helicopter manufacturers.

Aneto turboshaft engine family. In September 2017, Safran Helicopter Engines is unveiling its brand-new Aneto high power engine family. Designed for new super-medium and heavy helicopter market, it incorporates ground-breaking technologies, developed as part of the Safran Helicopter Engines R&D roadmap. Aneto family will feature several models covering 2500 to over 3000 shp power range (Figure 5.12) [5.39, 5.40].

First 2,500 shp model, named Aneto-1K, has been selected by Leonardo to power its twin-engine AW189K. An entry into service is scheduled for fourth quarter of 2018. Aneto-1K EASA certification will meet that timetable [5.40, 5.41].

The Tech 3000 technological demonstrator is a key building block of the Aneto family. It enables Safran Helicopter Engines to validate designs and technologies capable of delivering up to 15 % better fuel economy over today's high power engine models. Thanks to an exceptional power-to-volume ratio, it offers 25 % greater power (when compared to existing engines of same volume), as well as better performance in "hot and high" conditions, improved range and payload and reduced environmental footprint [5.41]. It is developed from the RTM322 (3 a + 1 c = 2 + 2): the -1K has a similar architecture but no common parts. Parts made by additive manufacturing are used in the gyratory combustion chamber and the inlet guide vane system. The new technologies will be gradually incorporated in the Aneto models, depending on the power requirements and entry-into-service timeframe. Compatible with hybrid and distributed propulsion systems, in cruise flight one of the two engines could be shut down and restarted when needed [5.40].

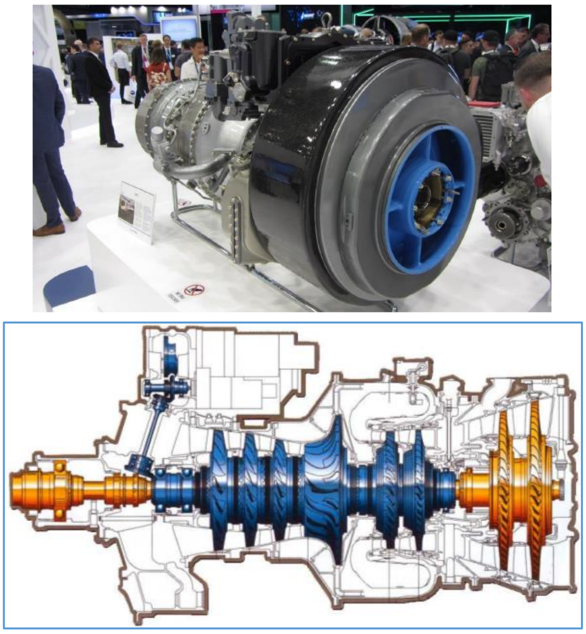


Figure 5.12: Aneto turboshaft engine

Aneto features higher reliability and safety. Its maintainability has been optimized with fewer scheduled maintenance tasks and longer maintenance intervals, and this new range will have connected features like health monitoring (predictive maintenance). Designed for next generation rotorcraft, Aneto is also a perfect drop-in engine solution for existing model.

T901-GE-900 & T900 advanced turboshaft engines. Within the framework of the Advanced Affordable Turbine Engine (AATE) project and the Improved Turbine Engine Program (ITEP), General Electric company and Advanced Turbine Engine Company, LLC (ATEC) developed the critical technologies and new generation turboshaft engines –T901-GE-900 (GE3000) and T900 (HPW300) with take-off power 3000 shp based on which they is supposed to develop turboshaft engines in the range of take-off power from 2000 to 5000 shp [5.42-5.45].

In the new engine, General Electric remained committed to the proven the T700 architecture based on a single-spool gas generator using an advanced technologies (Figure 5.13) [5.46-5.48].

- Compared with an existing T700 engine, the T901-GE-900 engine provides:
- 25% reduction of specific fuel consumption;
- 80% increase of power-to-weight ratio;
- 35% reduction of production & maintenance cost;
- 15% reduction of development cost;
- TBO not less than 6000 hours (15000 cycles for “cool” and 7500 cycles for “hot” part including combustor liner and HPT blades).

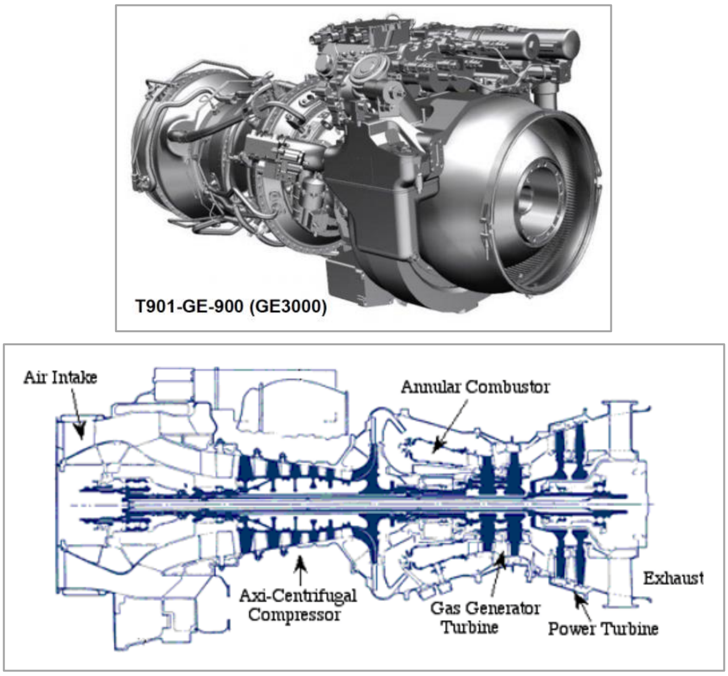


Figure 5.13: GE Aviation T901-GE-900 advanced turboshaft engine

Ceramic matrix composite materials are used in the engine design. This, along with an improved cooling scheme, allows to reduce cooling air flow rate, increase power, reduce specific fuel consumption and mass, and a new generation dust protection device that reduces the amount of sand sucked in, pressure losses in engine flowpath and an erosion of the turbomachineries and, thereby, increase the running time on the wing. Some of engine components are manufactured by additive manufacturing, which allows to reduce significantly an engine parts count, providing maximum reliability while reducing weight and manufacturing and maintenance costs.

An alternative version of advanced turboshaft was developed by ATEC [5.49]. ATEC T900 is created based on a two-spool gas generator, which, according to the company, in comparison with a single-spool one, provides (Figure 5.21) [5.44, 5.55, 5.50]:

- 10% greater opportunity to increase engine power;
- automatic load balancing between spools;
- an operation of engine components at lower temperatures;
- increase of engine life.

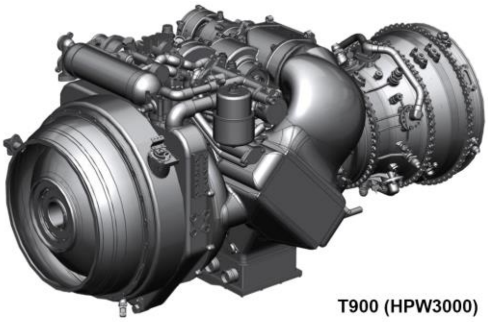


Figure 5.14: ATEC T900 advanced turboshaft engine

T408 turboshaft engine. To replace the T64 turboshaft engine, General Electric developed the T408 (GE38-1B) new turboshaft engine with a takeoff power 7500 shp In December 2006, the engine was selected by Sikorsky for the propulsion system of the CH-53K heavy helicopter. Compared to its predecessor the T408 has 57% more power, 18% less specific fuel consumption, 60% fewer parts and 50-80% less cost of operation. In addition, it provides increased resistance to sand and sea water and operation without restrictions on the stall margin (Figure 5.15) [5.51-5.53].

MTU Aero Engines (18% participation), which is responsible for the development of a power turbine, takes part in the work on the T408 engine as RRS-partner. Prior to this, this company participated only as a manufacturer of individual components for engines of US companies. This engine has the same architecture as the T700, but it uses advanced technologies that General Electric uses in its new military and civilian engines.

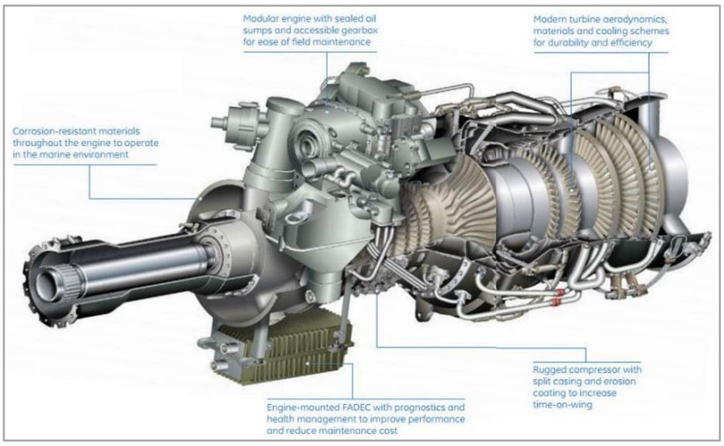


Figure 5.15: Cross-section of GE Aviation T408 turboshaft engine

In the T408 are used:

- axial-centrifugal compressor (5 axial blisk stages + 1 centrifugal stage) with improved aerodynamics of airfoils and an overall pressure ratio 18.6;
- low-emission annular combustor;
- 2-stage gas generator turbine and 3-stage power turbine;
- 2-channel FADEC control system with an integrated health monitoring system;
- new cooling scheme, structural materials and protective coatings to increase the life.

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Based on the results of ongoing work, engine companies are starting to create a new generation of engines, which in terms of performance will significantly exceed the engines in service and the technologies used in them will be aimed to reduce a cost of all components of an engine life cycle.

5.3 Prime movers - Existing propulsion systems

The previous paragraphs presented a comprehensive review of current core propulsion systems for regional aircraft. They are mostly turboprop engines, as they are the most suitable choice for cruise Mach numbers between 0.4 and 0.65 circa. In this range, they outperform piston engines, because of a lower weight and frontal area, and turbofans, thanks to higher propulsive efficiency, resulting from the lesser compression happening in a propeller disk than in a fan stage [5.54]. Turboprops are also more thermodynamically efficient than turbofans at given cycle parameters, because their power turbine extract further work from the exhaust, limiting the thermal energy exhausted. Other performance and noise benefit derive from the use of a gearbox to decouple the propeller and the core, and a blade pitch control system for off design operation. Many operative engines in operation have comparable features, hence a comparison is possible to extract reference figures. The bubble plot in Figure 5.16: Turboprop comparison combines three relevant features for some existing turboprops. Each bubble is proportional to the power rating of the engine. The overall thermal efficiency spans from 23% to 33%. The beneficial effect of bigger size is visible for the PW150, while the WJ-5 is penalised, possibly due to outdated design.

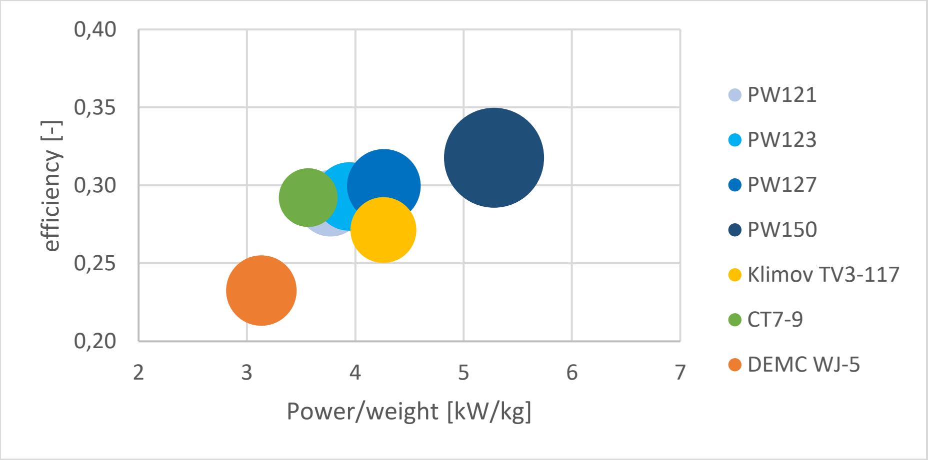

Figure 5.16: Turboprop comparison

A hypothetical state of the art engine would then be characterised by a power to weight ratio of 5 kW/kg, and an efficiency of 32% circa, corresponding to a power-specific fuel consumption of 73 μg/(Ws) at maximum power.

Turboprop engines do not reach particularly high turbine entry temperature (TET): 1250 K are estimated at take-off: designers prioritise the materials resistance to thermo-mechanical stresses, and easiness of manufacturability, to produce low-cost low-maintenance units [5.55]. This leaves a wide of design improvement in terms of temperatures, materials, pressure rations, and component efficiency. In addition, the clean-sheet design of all the models reviewed is not recent: adoption of current state-of-the-art solution can result into a significantly more efficient results.

Turboprops rely on a mature set of design rules and analysis tools. This makes a new full design quicker, and the certification easier, compared to innovative prime movers. Future standards for reducing emissions will likely aim at increasing the overall system efficiency. The adoption of a gas turbine (turboprop core) as prime mover for novel hybrid propulsion system is favoured by the maturity of these machines, their relative low development cost and established procedures for operation and maintenance.

Evolutionary trends can be extrapolated from comparison with turbofan research. According to NASA [5.56], technologies available by year 2040 involve:

- composite ceramic material in turbine blades, with an increase in TET and reduction in engine size. The existing trend suggest an improvement of roughly 10°C/year [5.57]. Extrapolation needs to be exerted with caution because of combustion limits and economic considerations, nonetheless TETs around 1400-1500 K would be possible at maximum power., core technologies also involve:
- improvement of components efficiencies, due to more advanced simulation tools, manufacturing techniques and use of active clearance control. Isentropic efficiency nearly to 90% can be assumed.
- General adoption of lightweight materials;
- Use of advanced combustor technologies (such as fuel staging) to limit NOx emissions

The structure of the machine will not necessarily change, unless overall pressure ratio suggests an increase of stage numbers or the addition of axial stages. Figure 5.17: expected future technology [14] summarizes expected area of improvement. Reference [5.56] estimates 41% reduction in cruise TSFC and up to 60% NO_X decrease on landing-takeoff cycle.

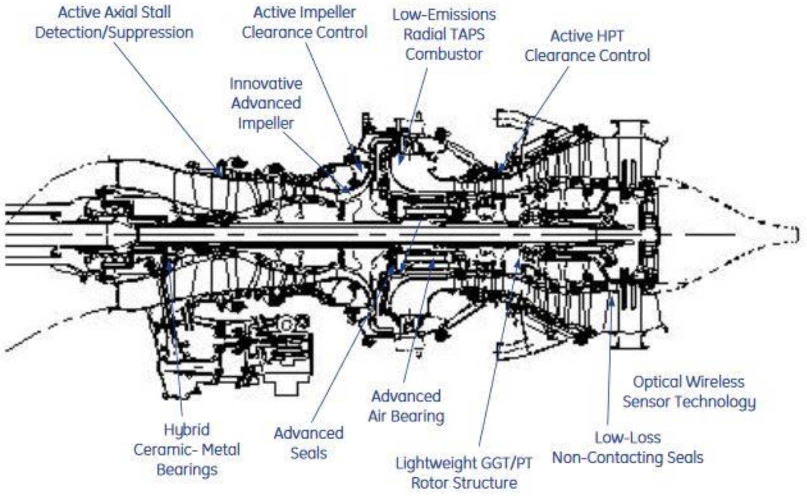

Figure 5.17: expected future technology [14]

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A likely set of parameters for advanced turboprop core is defined in Table 5.2:

Parameter	Value
Compressor efficiency	0.9
Turbine efficiency	0.9
OPR	20
TET	1400 K
Cooling air	5%
Thermal efficiency	39%
Specific power	280 kW/Kg/s
Compressor efficiency	0.9

Table 5.2: Future turboprop core design data

Turboprop-based propulsion systems can easily benefit from integration with electric technologies: the shaft power produced can be transmitted to a propellers array in a distributed propulsion configuration; it can be converted or integrated if the engine is coupled with electric motors or generators components in hybrid or turboelectric configurations.

5.4 Prime movers – Novel Cycles

While evolutionary approach has been generally followed in engine development, physic and thermodynamic reasons limit the potential benefit achievable using simple Joule cycles:

1. The maximum TET can be increased by using new high-resistance alloys/CMCs, improved cooling technologies and/or trading-off efficiency with maintenance cost; a ceiling is set by the chemistry of hydrocarbon combustion and material science.
2. The maximum pressure ratio is constrained by the compressor's last stage blade size. A turbomachinery layout change can result into higher complexity and weight;
3. The entropy generated in a constant pressure combustion is higher than compared to a constant volume process: combustion is a relevant source of thermal losses [5.58];
4. The efficiency of single turbomachinery components of the machine, which is close to their realistic physic limits;
5. The centrifugal stresses, limiting the maximum rotational speed and the size.

Figure 5.18 outlines the first three bullet points, independent of the physical size of the machine.

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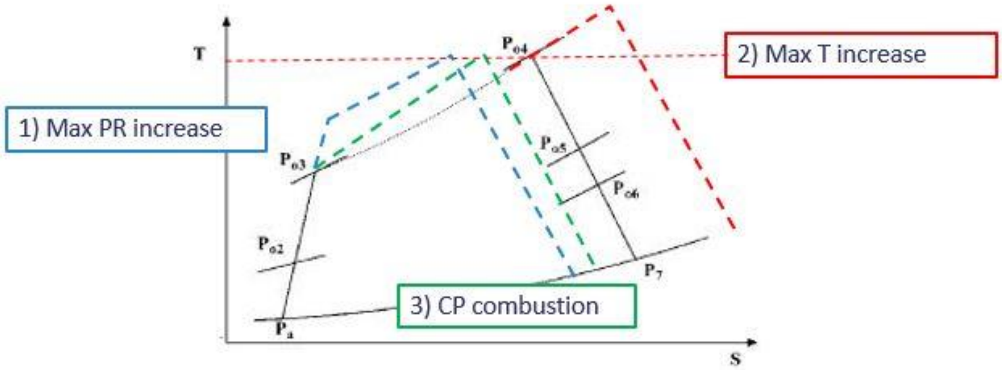

Figure 5.18: Option to increase prime mover efficiency on T-s diagram

Different thermodynamic cycles have been proposed as alternative prime mover. They mainly increase in efficiency, which connects directly to CO_2 emission and mission cost. They rely on one or a combination of the following strategies:

- Increase the maximum TET of the cycle;
- Inserting a topping cycle, which enhances or replaces the high-pressure shaft of the gas turbine, to increase the maximum cycle temperature and/or the maximum pressure ratio;
- Perform a more efficient constant volume combustion;
- Increase the specific work of the cycle through intercooling or reheating;
- Include recuperation through a heat exchanger.
- Increasing the component efficiency
- Extract as much heat as possible during the expansion;

Current turboprops address effectively the last point through their power turbine. Intercooling and reheat increase the specific work of the cycle, but do not improve its efficiency. Their use implies the adoption of extra components, with an unavoidable weight increase. Therefore, they are not investigated further. Also recuperated cycles are not considered, as they include heavy heat exchangers.

5.4.1 Wave rotor topping cycle

A wave rotor is a device in which two fluids exchange energy by direct contact and axial displacement. It is arranged as a set of cylindric channels, that spins between two stationary endplates, whose ports control the flow inlet and outlet flow. Both ends of each channel are periodically exposed to different pressures. The combined effects of pressure differential and rotation cause pressure waves inside the rotor channels, which compress or expand the flow to without being deflected by a blade or an impeller [5.59, 5.60]. Wave rotors found application in the automotive industry as turbochargers, but their application to aero engines is not mature yet.

The wave rotor can be integrated with a gas turbine as a topping cycle, as visualised in Figure 5.19. The wave rotor accepts flow from the compressor outlet (1), compresses it and redirects it to the combustion chamber (2). After the combustion process (3), the flow returns to the wave rotor for expansion (4), before being delivered to the turbine. Two configurations exist, through flow (left in Figure 5.19) and reverse flow (right). The former is preferred, since the direct contact of hot and cold streams improves the wall cooling: higher COT and TETs can be achieved with the same cooling air [5.60]. Several thermodynamic configurations have been studied for gas turbine topping:

- TET constant or COT constant: respectively higher peak temperature or lower thermal requirements for the turbine are achieved.
- OPR and TET constant: increased specific power reduces the size of compressors and turbines
- Unmodified combustor or turbine: lower pressure ratio or TET allow size reduction or lower maintenance cost.

Choosing a configuration depends on whether smaller size/cost, better efficiency or turbine life are required [5.61, 5.62]: each target is reflected on different combination of cycle parameters.

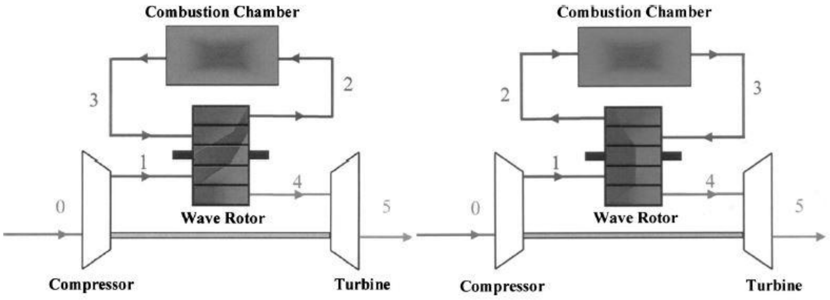

Figure 5.19: Wave rotor representation as GT topping cycles 5.62]

The advantages of wave rotor over a turbomachinery-based shaft are [5.60, 5.63]:

- Higher cycle thermal efficiency allowable, because of a combination of higher temperature and pressures. The former depends on the better cooling capability, guaranteed by the direct contact of hot and cold streams: material limits of the drum can be overcome. The latter is achieved as last stage blade height is not a constraint;
- Size and inertia are smaller, with associated benefits of reduced lag and components cost;
- The theoretical isentropic efficiency of a shock is higher than a compression via rotating machine, although the difference reduces with increasing pressure ratio: usual values are in the range 1.8-2.2;

Disadvantages include:

- A lower pressure ratio, compared to than a single centrifugal stage;
- Leakages due to a gap between rotor and end plates;

- A significant fraction (40-50%) of combusted gases are trapped in the rotor drum, reducing the effective volume available;
- The necessity of complex connection ducts, susceptible to high pressure losses;
- Efficiency reduction (5% circa) in the downstream turbine because of unsteady flow.
- Difficulty to simulate properly the internal flow pattern.

Equations and models to describe the performance of a wave rotor are provided by [5.64, 5.65]. The topping version with constant TET, and increased OPR and COT, is seen as most promising, to target as much efficiency increase as possible. It also allows to keep the component design unchanged, if the wave rotor tops existing turbomachinery layout. Replacement of the HP shaft is not recommended because of the low pressure ratio, compared to the standard centrifugal compressors.

NASA studied the potential benefit of integrating a wave rotor in gas turbines. In the layout described above, different engine sizes have been considered, finding SFC reduction of 17-20% and specific thrust increase of similar magnitude. The weight contribution of a wave rotor is circa 20% of the entire engine [5.66, 5.67]. Overall fuel efficiency can be estimated at 7% over a mission [5.60]. To extract the maximum benefit form a wave rotor, the coupling with a constant volume combustion is favoured, as even higher temperatures can be reached.

Relative to other technologies, the TRL level of wave rotor is higher, as its operation has been demonstrated. It is advantageous in terms of cost, as the device is not complex. Nonetheless, scaling up to MW-power levels yet needs to be performed, as well as its adaptability for flight conditions. Another issue is the mechanical integration, as current reverse-flow combustors and HP machineries need to be rearranged to leave space for the wave rotor.

5.4.2 Otto compound cycle

Piston engines are largely known for their use in the automotive industry, due to their simplicity, reliability, efficiency and good off-design behaviour. They are based on the reciprocating movement of a crankshaft system: within each working cycle, the air is first compressed as the piston movement reduces the volume of the chamber; fuel is added and combustion takes places; expansion and expulsion of the exhaust complete the cycle. Thermal energy is converted into mechanic displacement and transferred to the shaft during the expansion. The Otto cycle features fast constant volume combustion, initiated by an electric spark plug. In a Diesel cycle, the fuel-air mixture self-ignites after a threshold pressure: the process is slower, and the combustion is partly a constant volume and partly at constant pressure; higher pressure ratios are achieved in Diesel engines [5.68].

Piston engines have been the first prime movers used in aviation; today they power single-engine small aircraft. Most of the existing piston engine have cylinders arranged in a horizontal layout, staggered on the opposite side of a central crankshaft. Inline and radial layout also exists. Their main advantages over gas turbines are:

- Higher specific power and efficiency;
- Lower cost;

Conversely, they have been replaced by jet engines in larger aircraft due to:

- ☐ High weight and larger frontal area;
- ☐ Higher vibrations;
- ☐ Inferior performance at high speed and altitudes.

Existing models do not exceed a maximum power of 300 kW, with power to weight ratio ranging between 0.8 and 1.7 kW/kg with a thermal efficiency of 35-38% [5.54]. Reference [5.68] provides correlation for scaling engine power and weight.

While the technology is mature (TRL 9) *per se*, it is not suitable for the power ranges required by the project's requirements. Interest in piston engine arises due to possible synergy with current gas turbine: a topping combination would allow much higher overall pressure ratio, efficient isochoric combustion and greater peak temperature, without severe material requirements. Germany's Bauhaus Lufthart proposed a composite cycle configuration, where the Otto engine replaces the high-pressure shaft and the combustion chamber [5.69, 5.70]. Considering current engine cores, maximum cycle temperature of 2500 K and overall pressure ration of 40 are possible. Alternative configurations see the piston engine core providing shaft power in a separated arrangement. Figure 5.20 represents the combined arrangement for a turbofan.

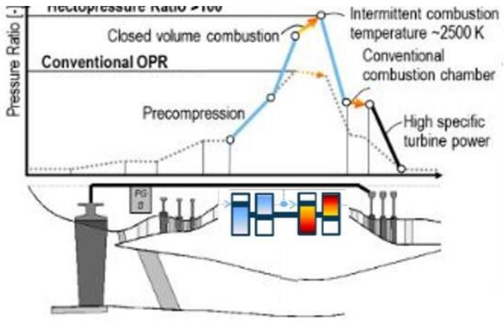

Figure 5.20: Layout of Otto topping cycle [5.69]

[5.69] found that at a given engine size, a 15% circa of SFC reduction is achieved compared to conventional engines, albeit weight increases by 30%. CO_2 emission reduces, because of higher efficiency, while NO_X production cannot be accurately modelled, but it is thought to be higher than today's values. A potential benefit is the increase of specific cycle work, which can be translated into a smaller core engine for a given power output. High delivery temperature following turbines can be mitigated with power offtake, which is a potential synergy. Piston engine components are manufactured with known technologies; therefore, engine recyclability would be good.

Achievement of TRL 2 for the technology is claimed, with a good outlook on further advancements, as the single components technology is mature [5.70]. Nonetheless, the research on the combination is at very early stages. The limited amount of research on the specific topic does not allow solid evaluation of a combined Otto-Joule cycle in the 1-5 MW power range: a proper study with integrated assessment would be desirable. From available data, fuel burn benefit is too small to justify the weight and volume increase, as well as the complicate layout of such propulsion system. A bulky piston engine would create integration problem. The weight increase is better mitigated for larger engines, where its fractional impact on aircraft's OEW is smaller. On a mechanical standpoint, piston engines rotate much slower than gas turbines, therefore their combination would require a separate shaft or a gearbox, increasing the complexity.

5.4.3 Nutating disc

The nutating disc (ND), is an engine that performs a thermodynamic cycle thanks to the nutation of a non-rotative disc in a chamber. A patent was filed in 1993 by MEYER [5.71], as standalone engines for UAVs. The simplest ND layout comprises a bi-conical disc mounted on a Z-shaped shaft, chambers for compression, accumulator, combustion, inlet and exhaust manifold, valves. The disc nutation (similar to the wobbling motion of a spinning coin) is responsible for the thermodynamic processes: air is admitted, compressed by reduction in chamber volume, sent to the combustion chamber, expanded on the opposite side of the disc, and exhausted. A test model and thermodynamic cycle are represented in Figure 5.21 [5.72]. Compared to piston engines, NDs have smoother torque curve versus crank angle, as they release power twice over a 270° shaft angle instead of a single/double 180° release; the centre of mass of the disk remains stationary, resulting in reduced bearing loads and sizes; the valves positioning can give different volumes for compression and expansion, allowing supercharging or extra expansion [5.73]. Double disc engine allows separation of compression and expansion room, alleviating the thermal loading.

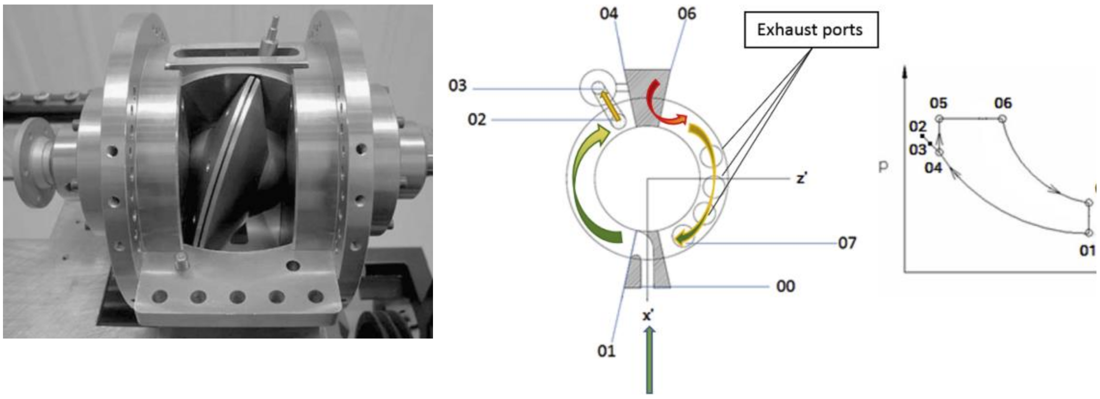

Figure 5.21: Nutating disc prototype (left) [5.73] and principle (right) [5.71]

For similar engine size and weight, the power output of a ND is roughly 4 times bigger than piston engines, but one order of magnitude smaller than gas turbines. ND is a competitive solution for power between 200-500 kW, where small size components penalise gas turbines. The ND is to use both sides of disc, reducing the required volume; different materials can be used on each disk side.

KORAKIANITIS presented a set of equation for the design performance of the single ND engine [5.73]. A 15" (318 mm) disk engine obtained a best thermal efficiency of 43% circa and power output of 350 kW; the optimal compression ratio is 15 with a peak temperature of 2600 K. Similarly to WR, different optima for efficiency and specific power exist. High peak temperature and large sizes favours high efficiency. The specific power is estimated between 2-3 kW/kg of mass flow. NASA tested two ND configurations [5.74, 5.75], a single and double disc, finding that a double disc can provide a power to weight ratio of 2.75 kW/kg. SEBASTIAMPILLAI [5.72] first integrated a double ND as a gas turbine topping for aero propulsion and provided equations for weight and size estimation. A 9% fuel burn estimation was estimated.

A stack of NDs would substitute the high-pressure spool of the gas turbine. A HP pressure ratio of 15 and a dedicated combustion system can improve the cycle thermal efficiency. CO_2 emission are reduced, but NO_X production increases. The physical integration of a ND stack is expected to be difficult, because a redesign of connecting ducts, the fuel and oil manifolds becomes necessary. The volume required by the stack volume can create further issues for small units. In a circumferential arrangement, each ND shaft would be offset from the main machine's rotation axis. While the technology has been tested and demonstrated in a laboratory, the level of TRL for high power and high-altitude applications is still very low. There is still very limited knowledge of the detailed performance of a nutating disc at off-design. Besides, there are no estimates of development costs, and comprehensive studies on key topics such as cooling, sealing and mechanical design. Despite some efficiency advantages on paper, it is concluded that the ND technology is not sufficiently mature to be combined to gas turbines in the power range considered.

5.4.4 Pulse Detonation Combustion Engine

Current cycles and engines all consider deflagrative combustion, where heat transfer and chemical reaction proceed at a subsonic speed. It is opposed to detonation, where the combustion front travels at supersonic speed through shock waves. Detonation is generally avoided in conventional engines, because the increased pressure developed may damage the engine, as the "knocking" in piston engines. Nonetheless, combustion technologies using pulsed detonation (PDC) received interest because they can develop much higher peak pressures compared to deflagration. The extreme velocity of the process adds the possibility of performing quasi-instantaneous combustion (constant volume), and to reach peak temperatures without compromising the material's life or thermal resistance. the theoretical advantage is shown in Figure 5.22 [5.76].

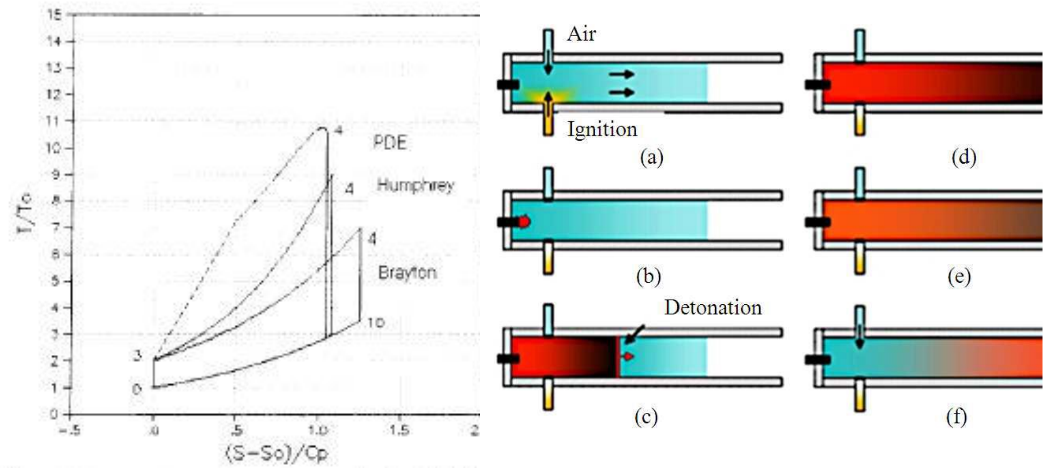

Figure 5.22: T-s diagram (left) phases of PDC (right)

A PDC combustor is a device with unsteady cyclic operation. It consists of a series of tubes, control valves, and ignitors. Each cycle comprises: filling of fresh air and fuel mixture (a);

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initiation and propagation of the supersonic detonation front (b-d); blowdown of a reflected expansion wave, lowering the pressure in the tube (e); purge of the exhaust (f) [5.77].

Standalone PDCs have mainly been considered for high speed and high-altitude application [5.78], including rockets and drones. More advanced applications involve the integration of a PDC in a gas turbine engine, where it replaces the combustion chamber. They benefit of higher specific work and efficiency compared to the Joule-Brayton cycle, due to the higher peak pressure achievable [5.79]. The advantages of the new cycle are:

- Increased cycle efficiency, due to the high peak pressure and temperature;
- Higher specific work;
- Simplicity, low manufacturing cost and weight of the combustor, particularly if the PDE's pressure rise also replaces the HP shaft;
- Reduced cooling requirement and thermal stresses on the combustor, due to the rapidity of the combustion.

Disadvantages include:

- High production of thermal NO_X and noise;
- Difficulty in starting of the detonation, and poor behaviour in deflagration-to-detonating transition;
- Development of appropriate injection and control system;
- Reduced efficiency of downstream turbine because of unsteady flow; Mitigation is possible using high detonation frequencies;
- Presence of shock loading on liners [5.80];
- Peak temperature is limited by allowable TET downstream.

[5.81] analysed the integration of PDC in a small turbofan engine for business jets. The estimated efficiency increases from 33 to 38% circa. [5.82] investigated the PDC integration into a larger turbofan, replacing the conventional combustor. Essential CFD modelling of the tubes are carried out to estimate NO_X and unsteadiness. A 5% better weighted SFC is found, reaching 2500 K and 80 bars at takeoff. The estimated weight is 9% of the total engine, with the engine mass reduced by 1.6% for given thrust output. These advantages are ousted by a prohibitive amount of thermal NOx and noise production, despite of the limitations of residence time. The building integration with current engines is relatively easy, with the only concern represented by increase in axial length.

To date, the only application of PDE was a small UAV prototype flown in 2008. Consequently, the TRL level of its integration with other devices is very low, with negative outlook on future development. The detailed analysis of the combined cycle and the testing are not present from the literature. Another major factor the penalises the PDC engine is the unavoidable increase of NO_X emission, which contrast with the limitation set ay ACARE without bringing in significant benefit in other performance metrics.

5.4.5 Solid Oxide Fuel cells

A fuel cell is an electrochemical device that converts the chemical energy of a fuel and an oxidizer into electricity. The single cell is composed of two electrodes (anode and cathode), an electrolyte, connecting and sealing materials. As displayed in Figure 5.23, fuel (typically hydrogen) is oxidized at the anode into H^+. At the cathode, oxygen reduces to O_2^- ions. The ions migrate through the electrolyte and combine with protons. Water and heat are created as by-products [5.83]. Fuel cells are stacked to increase the overall voltage provided. Current power range varies between 100 kW and 2MW for land-based application [5.84]. Studies on aerospace application of fuel cells do not exceed 150 kW and remain at a very low TRL level. [5.85, 5.86] investigated their standalone use for long-range UAV and small aircraft, where efficiency is more important than additional weight. Other applications of fuel cells involve independent power generation for APU and/or secondary systems.

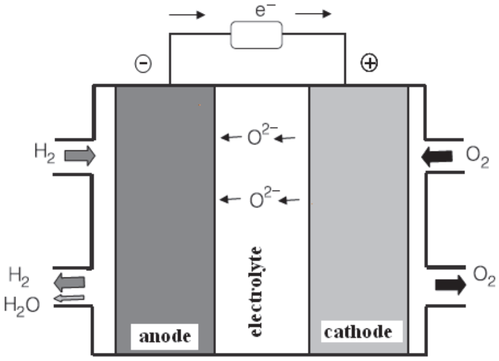

Figure 5.23: layout of a fuel cell [5.83]

Combination of fuel cells and prime movers involves the use of Solid Oxide Fuel Cells (SOFC), as their operating range (500 to 1000°C) integrates well with turbomachinery components: SOFC can be placed after or between the turbines, as in Figure 5.24. Advantages of SOFC combined cycle are:

- High overall efficiency, 50-60%;
- Direct production of electricity from fuel;
- SOFC can burn any hydrocarbon fuels, not only hydrogen;
- Limited cooling and thermal management requirement good durability

On the other end, the disadvantages include:

- Very low gravimetric and volumetric power density (0.32 kW/kg and 0.33 kW/dm^3 respectively) [5.87];
- Relative complex control and fuel feed system;
- Thermal expansion issues limit response at start-up and transient;
- Low voltage provided – cell stacking required.

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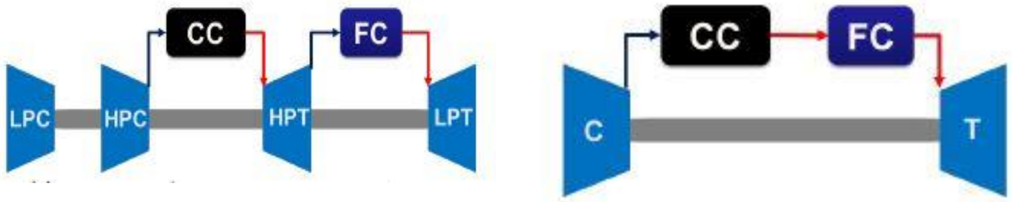

Figure 5.24: Integration of a SOFC into a gas turbine [Gallo, 2015]

GALLO [5.88] studied two integrated layouts for gas generators. Low fuel-to-air ratio and voltage around 0.8 V yield the best combined cycle efficiency, 51% circa with an OPR of 10 and a maximum temperature of 1000 K for the configuration on the right of Figure 5.24. The optimum cycle efficiency is related to cell voltage, which in turn is a compromise between fuel cell and turbine temperature requirements. COT does not exceed 1100-1200 K because of said trade-off. No benefit is found at the aircraft level, as the higher efficiency is offset by the weight increase, even with optimistic assumptions on technology development.

A SOFC combined cycle presents good synergies, as it matches well with temperatures and pressures found in gas turbines, and directly produces electric power. Nonetheless, it cannot be considered a viable solution for prime movers because of its weight and low TRL level. The technology remains interesting for secondary power system.

5.4.6 Qualitative assessment

This section provides a basis for technology evaluation. The choice of a prime mover technology relies on a series of different criteria, sometime contrasting each other.

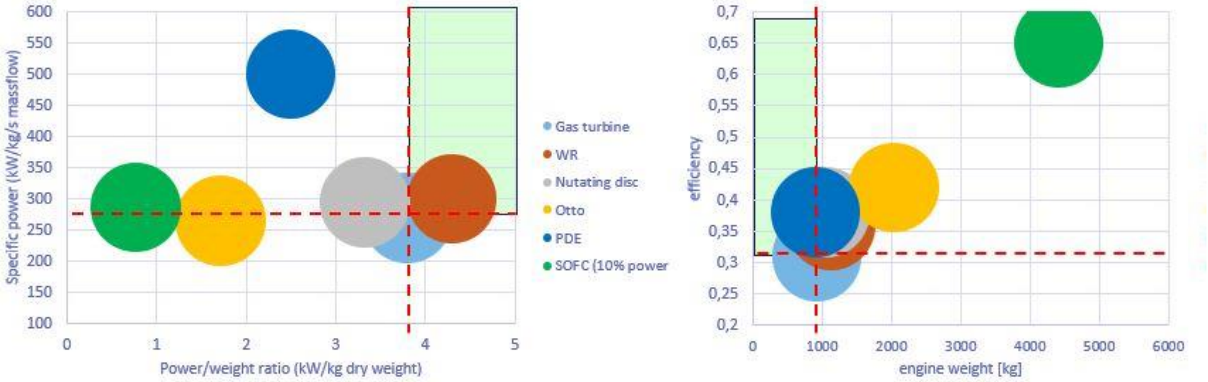

Figure 5.25: Novel cycle comparison

Figure 5.25 plots the cycles of section 5.4 according to common metrics. The hybrid SOFC is bound to provide 10% of the output power, to limit weight penalty. The bubble size indicates a range rather than a specific value, because of the uncertainties associated to each technology. Red lines and the light blue bubble mark the available technology, based on simple gas turbine. Novel designs need to be in the green areas to present significant advantage. On the left, all cycles have a specific power comparable with the reference. The PDE engine is an exception as detonation can release more energy for given mass flow. Proposed cycles generally include heavy components, which lower the power to weight ratio. Only wave rotor seems to offer a marginal improvement. The right plot compares engine weight and cycle efficiency. Efficiency is the main advantages of novel cycles: with the exception of hybrid SOFC, the improvement is of just few percent, counteracted by weight increase. The use of fuel cells is an outlier as it can reach efficiency of 65%, but at the expense of weight. Figure 5.25 data are obtained assuming 3.5 MW design power output. The following metrics are evaluated:

- ☐ Efficiency;
- ☐ Power to weight ratio, to consider the weight and the dimension implications as well;
- ☐ Emission, including CO_2, NO_X and noise;
- ☐ Complexity of the engine and mechanical integration;
- ☐ Life of the components, that can affect maintenance cost;
- ☐ Scalability to include how different technology can fit different power requirements.

Table 5.3 present the scoring for each technology and metric, in respect to the reference. 0 is the default value, positive (or negative) scores indicate small or considerable improvement (or worsening) compared to current prime mover.

Cycle	Efficiency	Power/weight	Emissions	Complexity	Life	Scalability
Gas turbine (current)	0	0	0	0	0	0
Wave rotor topping	+1	0	0	-1	0	-1
Otto compound cycle	+1	-1	0	-3	+1	-3
Nutating disc topping	+1	-1	0	-3	-1	-3
Pulse detonation combustion	+1	+1	-3	0	-1	-1
Hybrid fuel cell	+3	-3	3	-1	-3	-1

Table 5.3: Novel prime mover scoring

It appears that novel cycles benefit mostly from a modest efficiency increase, but they are disadvantageous when other requirement of a propulsion systems are examined. While CO_2 emissions reduce, NO_X increase according to peak cycle temperature. The basic gas turbine engine remains as the simplest machine, and with less integration problems including layout, flow unsteadiness, accessory control systems. Scalability also affect some of the technology, which are advantageous at specific power class or at certain rotational speeds. In conclusion, no technology presents enough benefit to justify its adoption as prime mover. TRL is assessed separately. Novel technologies are penalised by low TRL (3 or less). Technologies such as piston engines and fuel cells are in use today, but their application for aircraft propulsion in combination for gas turbine has not been assessed beyond preliminary studies. Only the wave rotor as topping cycle is at TRL 4. No cycle is expected to reach high TRL for year 2040.

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6 Electrical Machines & Power Systems

6.1 Electrical machines

6.1.1 Types of electrical machines

Electrical machines could be divided to the next groups by type of operation. First is synchronous machines (SM). They are often used as generators. But in recent times synchronous motors also become very popular due to development of new types of controllers for them. Synchronous machines can have excitation with field windings (called wound field) and permanent magnets. Besides synchronous machines without excitation are known. Such machines called reluctance and hysteresis. They also have some advantages. Asynchronous machines are the most popular motors due to their simple construction and simple controllers. But they have lower value of specific power and efficiency in comparison with synchronous machines. Direct current machines have a lot of advantages but they have brush contact which decreases their efficiency. Besides its forbidden to use contact machines in airplanes with altitude more than 4000 m. In this case BLDC (contactless brushless) machines become very interesting. In general this is synchronous machine operating together with power electronic module. It means that this type of machine has design of SC and control characteristics of DC machine. Transformers are used to convert AC voltage from one value to another with constant frequency [6.1].

Of course every type of machine could have different number of phases, pair poles, rotation speed and etc. These parameters connected with application of machine and influence its dimensions and weight.

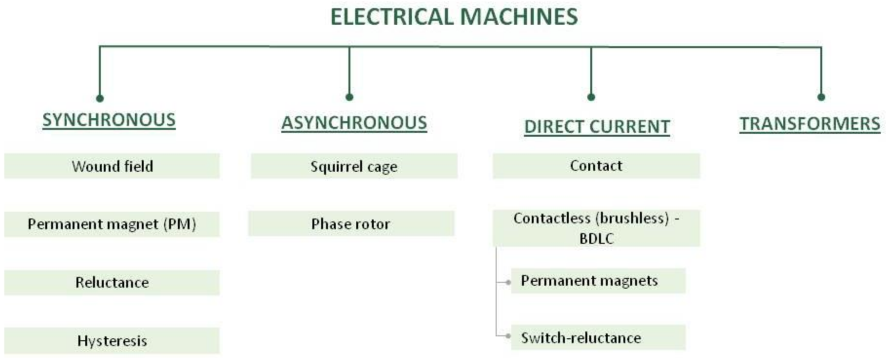
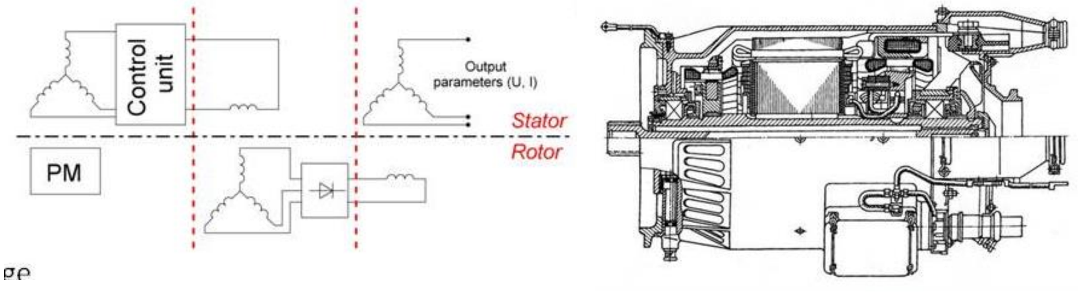


Figure 6.1: Types of electrical machines

Aviation generators

Modern aviation generators are example of complex and efficient devices. It consists of three machines which all are SM machines and called sub-exciter, exciter and main generator. This type of machine has next advantages: autonomous, possibility for regulation, possibility of overload, reliability, possibility to realize starter regime, constant and variable output voltage. But disadvantages are very serious: complex construction and heavyweight. Combination of advantages and disadvantages allow to use them as main generators for the biggest passenger aircraft B787. These machines have very intensive oil cooling. Nevertheless they have less than 3 kW/kg. It is connected with range of rotation speed (from 7200 to 16000 rpm) and requirements for output voltage. In other word generator should provide power for minimum rotation speed and satisfy mechanical requirements for max speed. In this case it seems to be very difficult (maybe even impossible) to increase output power and specific power of such machines using existing architecture of electric system of airplane [6.2].



a) b)

Figure 6.2: Aviation generator: a) – principal scheme, b) – example of the generator

New architectures

The same conclusion is made by specialists of Thales – the world known electrical machines producer. You can see different architectures of aircraft electric system. Promising is HVDC system. The main idea is to produce energy by AC generators then transform it to DC and distribute. It gives opportunity to uncouple parameters of generator and loads and in turn decrease requirements for generator. You can see comparison of specific power of generator in different networks. If we will go to constant rotation speed we can achieve 7 kW/kg for aviation generators. But it will be another type of machine than wound field [6.2].

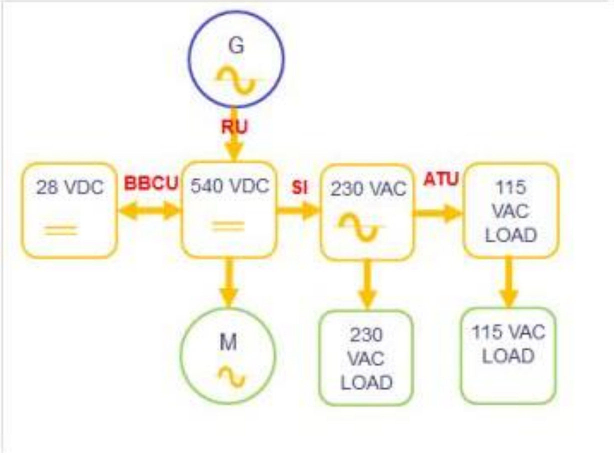


Figure 6.3: Promising architecture of electric system

6.1.2 Permanent magnet machines

In HVDC system machines with permanent magnets (PM) look very promising. It is connected with its simple construction, high energy of modern PM, mechanical properties of rotor and etc. Rotation speed could be increased up to 60000 rpm and more thank to simple rotor construction.

Main disadvantage of machines with PM is absence of possibility of regulation. It is very important if machine operates as generator. Several techiques are known to provide regulation

of machines with PM but it make construction more complex, increase weight. Besides value of regulation is limited by 30%.
When machine operates as generator short curcuit can occur. It will be very dangerous becouse you can't decrease excitation like in wound field machine.
Of course PM machines can be used both as motor and generator [6.3, 6.4].

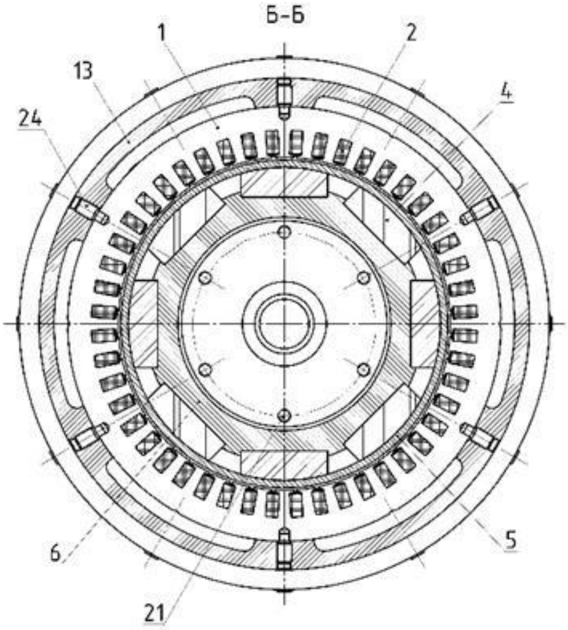


Figure 6.4: Example of construction of the machine with permanent magnets.

1 – stator core, 2 – slot, 4 – PM, 5 – bandage, 6 – rotor core

6.1.3 Permanent magnets

Modern permanent magnets are characterized by two values: magnetic inductance and coercitivity. Then bigger these values than better magnets. It is important to note that parameters of magnets decrease if temperature increase. Besides outer magnetic field demagnetize PM. It means that we need to choose proper parameters of magnet taking into account operating temperature and armature influence of the machines. Modern finite element modeling applications allow to do it automatically using demagnetization curve. For modern PM Br=1.5 T, Hc= ~ 900 kA/m.

Dependency of PM parameters on temperature looks very interesting. Figure 5 shows the most ration temperature range of use of PM. You can see that NdFeB magnets which have the highest parameters today have limited range of application temperature. But SmCo and PR magnets looks very promising for cryogenic temperatures [6.5, 6.6].

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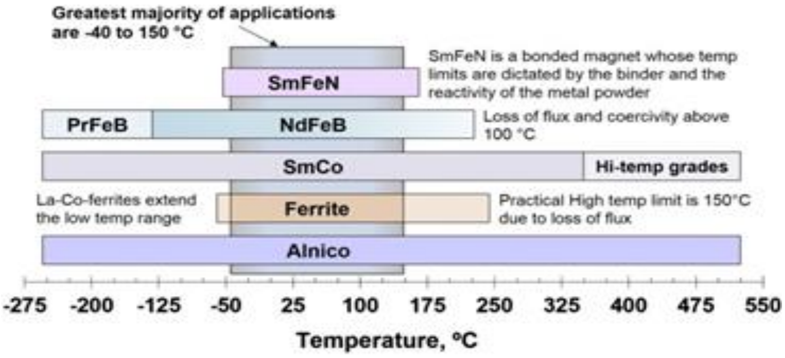

Figure 6.5: Temperature range for different PM

6.1.4 SC machines

If we talking about principally new systems such as hybrid propulsion systems electrical machines with extremely high specific power are needed. In this case superconducting technologies can be a solution. Today high temperature superconductors (HTS) are thin tapes and bulks. Application of HTS windings in electrical machines allows to decrease its weight and dimensions. Using HTS materials 20 kW/kg could be achieved. Operating temperatures could be different but less than 77K (liquid nitrogen). Current capacity of HTS materials increases with temperature decreasing. The most promising is application of HTS windings operating at 20K (liquid hydrogen). Parameters of HTS tapes has nonlinear dependency on temperature and external magnetic field. In this case design of HTS machines become more complex due to extra nonlinear dependencies.

Coupling of HTS electrical machines and cables open the way for development of principally new systems. Besides some researches of power electronic devices cooling with cryogenic liquids are known. Development of such devices will allow to design fully cryogenic system with extremely high specific power [6.7-6.9].

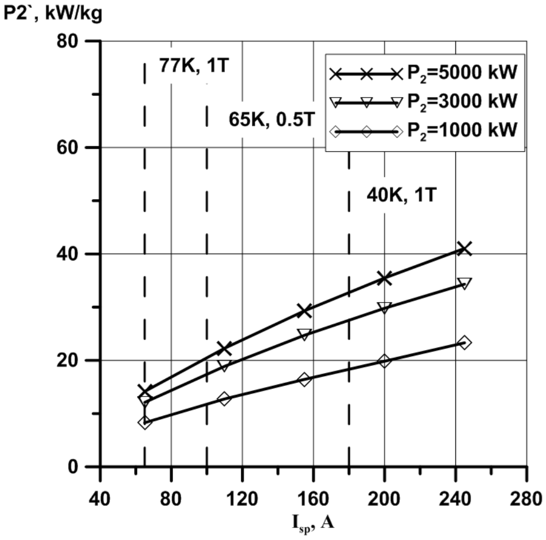

Figure 6.6: Specific power dependency

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6.1.5 State-of-art

It is known that each electric motor and generator have nominal (long time) and peak (short time) power. LaunchPoint Technologies is US company which key R&D areas are: hybrid system architectures, motor drives, generators and motors with high specific power, batteries. Their disk-type motor has 5.2 kW, 6000 rpm and air cooling. Their proposed 1MW motor looks very interesting but still they have not presented it anywhere [6.10].

Figure 6.7: LaunchPoint motor

Milandr-SM is Russian company which produce electric motors, controllers and batteries. They have two motors for aircraft application. Both are brushless DC motors with PM. Peak power is 25kW and 75 kW, rotation speed 2400 rpm [6.11].

Figure 6.8: Milandr-Sm motor

Siemens have demonstrated aircraft motor with 250 kW, 2500 rpm and 50 kg. Rotor consists of Halbach array and bandage. Double stator construction allow to increase output power but it also increase weight. In general high specific power of this motor is connected with effective cooling system and the feature that it does not have one bearing shield. Of course this machine is very promising and interesting for us as for machine designers [6.12].

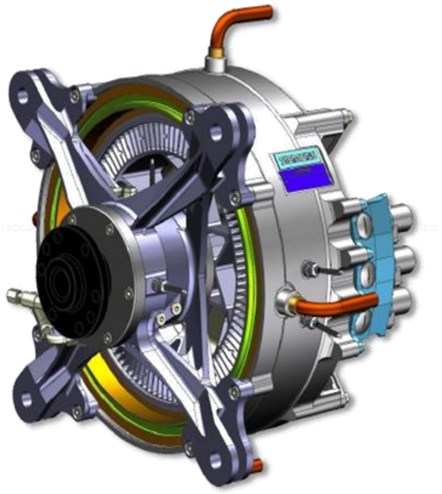

Figure 6.9: Siemens motor

Machine by ROLLS-ROYCE was presented during MEA 2017 conference. It was designed for 270V DC network of small civil turbofan aircraft. This is PM machine. Two windings on stator provide higher reliability due to double reservation. This machine operates with power converter. The dual channel 2-level converter topology with a paralleled DC link is used to drive the PM Starter/Generator is. In order to support the starting and generating functionality the power converter is required to operate bidirectionally. Hybrid power modules with Silicon IGBTs and Silicon Carbide (SiC) diodes were specifically developed by Semikron and implemented in the power converter [6.13].

Figure 6.10: Starter-generator by Rolls-Royce

University of Nottingham has very strong department of electrical machines and power electronics. These machine has 46 kW output power and 32 rmp. High rotation speed require strong fixation of PM on rotor. Here carbon Fiber is used. This machine is also design for 270 V DC network. The three-level converter was selected as the candidate power electronic converter to drive the high speed machine. The three-level converter is found to achieve the lowest heat-sink size and weight. This was mainly due to its ability to produce high fundamental frequencies with relatively lower switching frequency. This feature is particularly found to be

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advantageous due to the high fundamental frequency associated with the high speed machine [6.14].

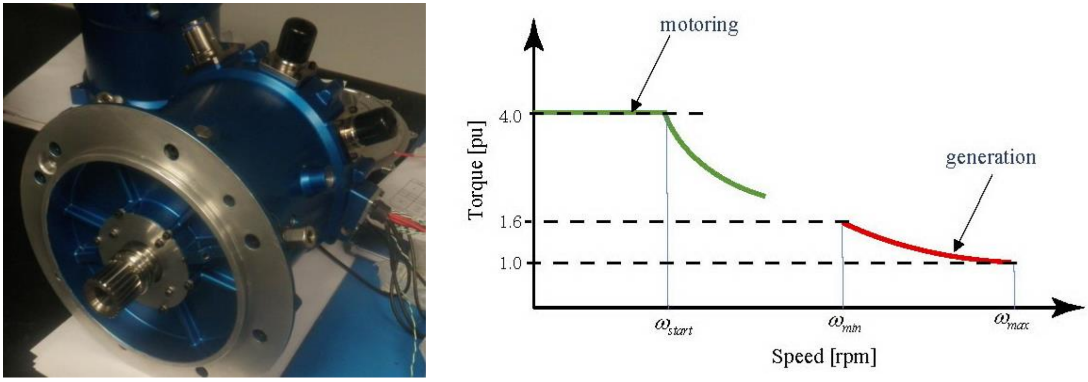

Figure 6.11: Starter-generator by University of Nottingham

In Ufa, Russia high speed generator was developed. It has two-pole rotor with PM and slotless winding on stator. Application of twisted stator core made of amorphous alloy allow to decrease losses in the machine. This machine was designed as generator for direct drive from gas turbine [6.15].

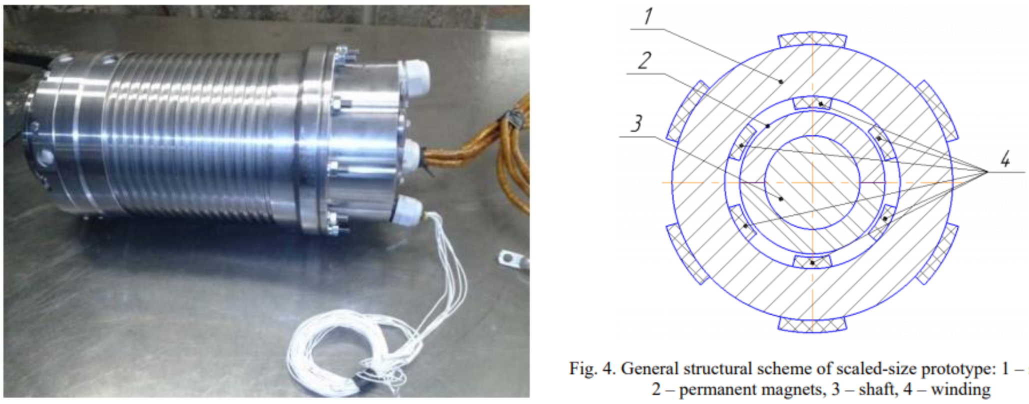

Fig. 4. General structural scheme of scaled-size prototype: 1 – stator, 2 – permanent magnets, 3 – shaft, 4 – winding

Figure 6.12: High speed generator

The 5 kW BLDC drive system motor for actuator for controlling the flap position of the aircraft has been created in MAI. This machine have rotor with PM. It is equipped with brake. Machine has air cooling Lab tests of the prototype were done, which confirmed the basic requirements of the technical specifications for this product.

Figure 6.13: 5 kW BLDC drive system for atuation system

6.1.6 HTS machines

Application of HTS AC windings needs experimental research due to nonlinear properties of HTS material. That is why only small-scale prototypes of such machines are exist in the world. In MAI, Russia several examples of such machines have been already developed. Using experimental data analytical techniques were improved [6.16].

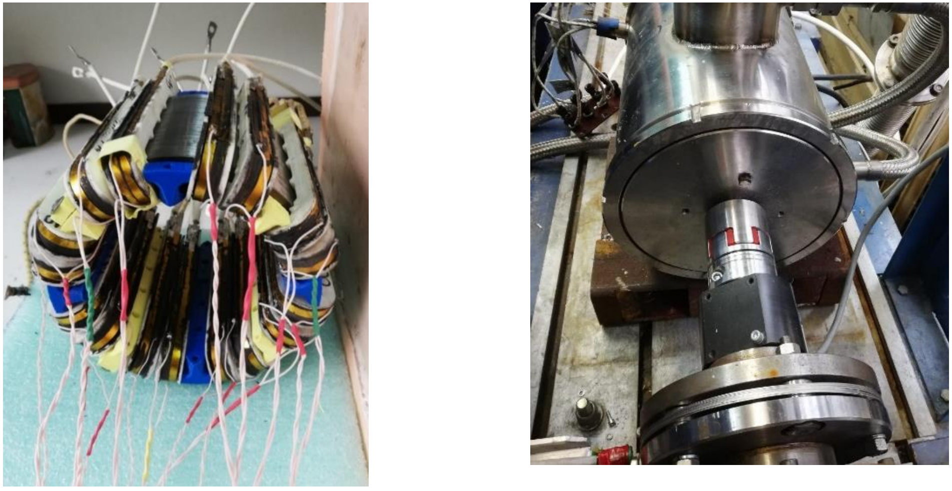

Figure 6.14: Electrical machines with AC HTS windings

Several years ago three machines with DC HTS windings were developed, manufactured and tested in MAI. Operating temperature of HTS windings is 77K. These machines has 1 MVA, 960 kVA and 200 kW output power. So it is rather big machines. 1MVA generator machine has HTS rotor winding and copper stator winding. Cooling system consists of rotating cryostat and channels inside the rotor. 960 KVA generator has combine excitation. The topology of generator is based on constructive schemes of brushless synchronous machine with claw-shaped poles. Copper field windings are replaced with windings from HTS 2G tape and new construction of claw-shaped rotor with permanent magnets is developed. The armature of this generator doesn't differ from armature of conventional synchronous generators. But magnetic field distribution in active domain is three-dimensional because of specific rotor construction [6.17, 6.18].

Figure 6.15: Comparision of 1MVA HTS generator and conventional one

Figure 6.16: 960 kVA HTS generator with combine excitation

6.1.7 Conclusion

In recent times specific power of electrical machines and power electronic modules have increases thanks to improvement of material properties, increased efficiency of cooling systems, increased clarify of calculation methods and so on. The highest values of specific power possess HTS electrical machines. But each application has special requirements. Each task could be solved using several solutions. To provide the best one we need to take into account all requirements which could be different for different applications. Therefore to have the best solution maximum initial data should be provided.

6.2 Electric distribution

An aircraft power distribution system with a HEP is one of the important and basic systems for the transmission of electrical energy from sources: electric machines, batteries, and possibly supercapacitors, fuel cells, solar panels and others to energy consumers: prime movers, aircraft systems and avionics. The main actuators of the distribution system are contactors, which can have various design and operating principle. Distribution system can be managed by flight management system or by other high level system.

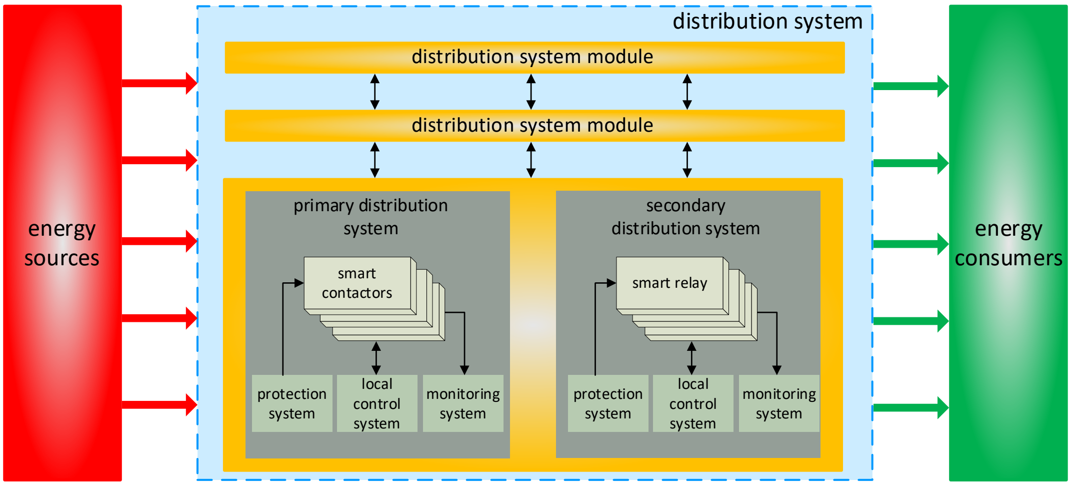

Figure 6.17: Electrical distribution layout

The mass of the distribution system depends on the power of the HEP. Since the power of the HEP of a regional aircraft is quite high, and it is necessary to ensure the safe operation of the distribution system, so the mass of the distribution system has a significant effect on the layout and general characteristics of the HEP and the aircraft overall.

In addition, the distribution system generates heat that must be reckoned with. Hence, the heat balance of the distribution system must be taken into account when designing the thermal management system.

6.2.1 Traditional electric distribution and challenges to HEP electric distribution

The power distribution system of an aircraft with a HEP is very different from that of a conventional aircraft. The differences are as follows:

Separability

On an conventional aircraft, a single distribution system consisting of subsystems: AC, DC, essential network, main network. On an aircraft with a HEP, there are at least two networks: electrical propulsion network (high, non-standard voltage) and non-propulsive electrical systems and avionics network (standard voltages). There must be an interconnection between the networks. So distribution systems can have significant differences, both in terms of power distribution of energy and voltage level.

Functionality

On a conventional aircraft, electricity is distributed to the needs of functional systems (control system, landing gear, avionics, etc.). On an aircraft with a HEP, the energy in the HEP network is distributed in order to ensure the functions of the HEP: moving, harvesting, charging. The energy in the avionics network is distributed to the needs of functional systems as control system, landing gears, computers cabin, etc.

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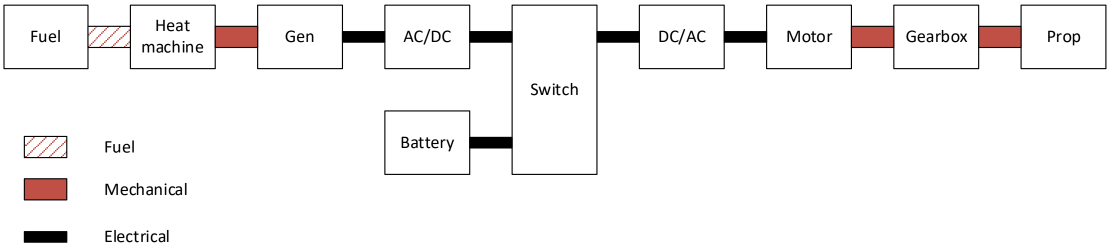

Figure 6.18: Simplest architecture of electrical system of HEP

The operating modes of HEP and of distribution system can have a larger list in comparison with distribution system of conventional aircraft, for example:

- ☐ Generation and using electrical energy (generator → motor);
- ☐ Generation and using electrical energy (battery → motor);
- ☐ Combination of previous two (generator and battery → motor);
- ☐ Generation electrical energy and charging batteries (generator → battery);
- ☐ Harvesting electrical energy (motor → battery);
- ☐ Starter mode (battery → generator) to start heat machine;
- ☐ Stand-by;
- ☐ Changing mode;
- ☐ Ground charging.

Bidirectionality

The listed modes show that almost every part of HEP can have bidirectional mode. For instance: generator can be motor, motor can be generator, battery is discharged and charged, AC / DC can be rectifier and inverter. Hence distribution system should be also bidirectional. It's challenging because of conventional aircraft's technologies generally do not provide for bi-directional power transmission.

Standardization

On conventional airplanes, energy sources and consumers, as a rule, have standard interfaces, voltage levels, and a degree of safety. On aircraft with HEP the design, power, voltage level, both of sources and consumers – prime movers, will depend on the design of the aircraft and the architecture of the HEP. In this case, the voltage level will correspond to the range of standardized levels. This statement is confirmed by the standards being developed: SAE AIR7502 – Aerospace Electrical Voltage Level definitions, SAE AIR6127 – Managing Higher Voltages in Aerospace Electrical Systems. A document SAE AIR7502 - Aerospace Electrical Voltage Level definitions has status work in progress and will be published in a while.

Safety

Electrical systems functions of HEP are not the same as electrical systems functions of conventional aircraft (e.g. Energy transfer for Lift and Thrust). Current regulatory framework (CS-25 25.1351-1365, MIL-STD-704F) is not applicable for electrical systems of HEP. Failure modes will not differ for conventional components, however due to innovations related to electrical propulsion, the failure rate of components will be different, in addition, new components can be used. The approach for safety assessment of aircraft with HEP should be the same as for conventional planes and it is based now on SAE ARP4754A.

Novelties

There can be some uncertainties and novelties in distribution systems in order to match top level aircraft requirements. For example they are: high voltage (arc, corona, propagation to low), higher current/power (heat dissipation needs), high EMI, bidirectional modes (motoring & regeneration), new components as pyroswitch/pyrofuses, fuel cells, cryogenics, hydrogen fuel and others. That should be taken into account to design a distribution system.

6.2.2 Technology state of art highlights and gap analysis

The aircraft distribution system with HEP can be implemented as a modular distributed system, with information exchange, which will allow integration into a single distributed load control system. Then the functions can be:

- Duplication (redundancy) of power channels of homogeneous equipment;
- Onboard diagnostics of power lines (monitoring for open circuit, short circuit, arc, corona discharge);
- Parameterization of power outputs for current and voltage;
- Re-commutation of power lines;
- Balancing power distribution.

To meet the high-level aircraft requirements developed in WP2, the following technologies are likely to be used:

- Integration of the distribution system with generation and consumption system, with the thermal management system, with flight management system;
- Localization of load centres;
- Energy management with high voltage levels;
- Compliance with safety requirements.

As mentioned above, the functions of the electrical system of HEP differ from the functions of the electrical system of conventional system, therefore, the functions of the distribution system of the electrical system of HEP differ from the functions of the distribution system and may have the following list:

- Reception of electricity from sources (generators, batteries, fuel cells);
- Transmission of electricity to the consumers of the GSU (main motors, starting motors);
- Optimal distribution of energy between sources and consumers in terms of energy consumption stored in batteries and obtained during fuel processing;
- Redistribution of energy reception in case of source failure;
- Redistribution of power transmission in case of receiver failure;
- Monitoring the state of energy sources;
- Monitoring the status of energy receivers;
- Reconfiguration of the distribution system in case of failure of the modules of the distribution system;

- ☐ Power transmission to the avionics system;
- ☐ Ensuring a balance of generation and consumption of energy.

To improve the efficiency of the mass-energy characteristics of the distribution system, the following technologies can be applied:

6.2.2.1 Modularly scalable electrical energy converters

Modularly scalable power converters, building easily scalable modular power conversion and distribution systems. Implementation of the technology will require the use of hybrid power semiconductor modules [6.19-6.22]. Modularly scalable power converters are designed to build easily scalable modular power conversion systems that provide high reliability, simplicity and ease of maintenance under the control of a single controller. To implement this technology, it is necessary to use integrated power modules in the development of aircraft power converters.

The power module should allow converting energy in two directions in order to implement the main mode - the operation of motors to create thrust, as well as for the mode of harvesting energy when taking energy from the motors when air plane has flight like descend. TLR in aviation is about 7-8.

6.2.2.2 Information interaction through power (PLC-technology)

Power line communication systems, will reduce the number of data buses in the power distribution control system [6.23-6.25]. The integration of systems and units provides for close cooperation in the development of a platform that includes systems such as flight control, hydraulic, fuel, air conditioning systems, power supply systems, gas turbine, including information interaction. The use of communication technology over power lines for data transmission over a high-voltage DC network for functional systems makes it possible to increase the degree of integration of information and functional systems. The PLC communication approach eliminates the need for digital data bus wiring by modulating data on power cables that run between the flight control computer and the control devices.
Aviation PLC technology is optimized to meet the needs of the aviation world: strict deterministic and reliable communication, environmental conditions relative to RTCS-DO 160, and filtering and data transfer functions
Current TLR is 6. It is widely used in electric power industry.

6.2.2.3 Liquid cooling systems

Liquid cooling systems, providing cooling of the power elements of the distribution system due to liquids with high heat transfer coefficients and heat capacity. TLR is 9.

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7 Certification

7.1 Introduction

Certification plays a pivotal role in aviation. Through experience a thorough set of rules and regulations have been established that allow aviation to operate as safely as it does. These airworthiness requirements are a result of 50+ years of conventional aviation and pose a challenge to innovation, especially to novel propulsion techniques and aircraft architectures. Because these requirements are the result of conventional aircraft design it can be difficult to certify novel concepts. This is not a bad thing, although this approach may be conservative, it prevents immature innovations from flying. The challenge is to use the existing certification framework to show an innovation is airworthy. This chapter explores the process of certifying novel aircraft architectures and concepts and concludes with a certification roadmap for hybrid electric aircraft.

7.2 Scope of certification process within FutPrInt50

Through certification one demonstrates via an appropriate assessment that the design of the product complies to a set of minimum accepted airworthiness and other necessary requirements. A product or part is airworthy when it conforms to its approved design and is in a condition for safe operation. To arrive at an airworthy product the process in Figure 7.1 is followed. The involvement of the airworthiness authorities (AA) is shown and it should be apparent that the authorities are involved in the development process as early as the design phase.

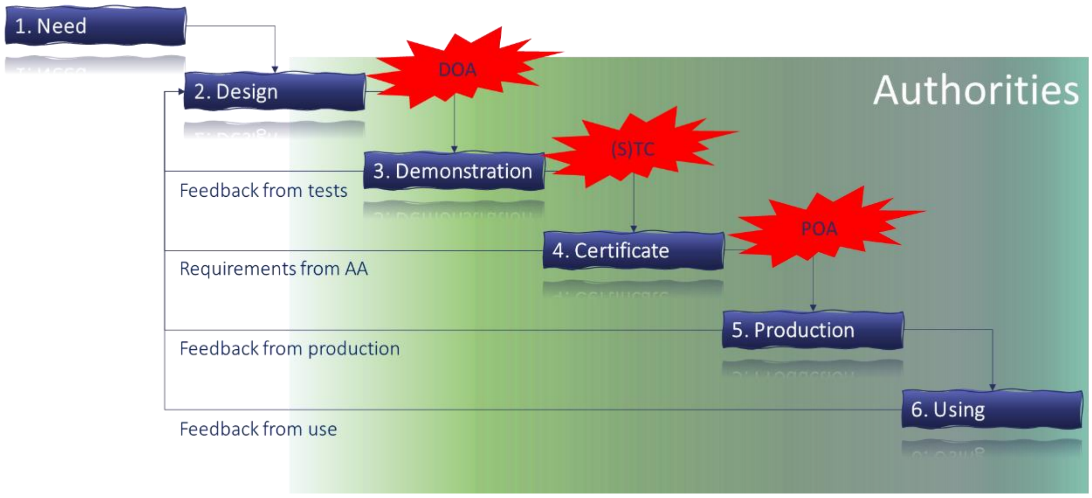

Figure 7.1: Certification process

The FutPrInt50 project focusses on the Need and Design step for the development of a Hybrid-Electric Aircraft. The FutPrInt50 product is a study with a major focus on heightening the TRL level of HEA and does not have the aim of producing an airworthy product. Therefore, the actual authorities are not directly involved. However, investigating the certification process is critical for this aim.

7.3 Certification aspects and terminology

Certification is the process of demonstrating compliance to airworthiness requirements. So what do these requirements look like? EASA has defined a number of books in which airworthiness requirements are collected. For our purposes the appropriate book to look at is CS-25. CS-25 is the Certification Specification for Large Aeroplanes. Within this specification, the requirements the 50-seater FUTPRINT50 aircraft should meet, are collected. With these requirements comes an abundance of so-called Acceptable Means of Compliance (AMC), which give the applicant guidance on **how** to show that your aircraft complies with the requirements.

As mentioned in the introduction the current airworthiness requirements are constructed for conventional aircraft. To be able to obtain a type certificate for a hybrid electric aircraft, which is a proof of meeting all airworthiness requirements, the CS-25 cannot be entirely used in its current form. Rather, modifications, addendums, and omittances are necessary for the CS-25 to be usable. Some requirements may be perfectly applicable to HEA, but the method of showing compliance could be different from the current state of the art. Therefore, alternatives for the AMC may be necessary, as these are often highly related to certain technologies.

7.4 State-of-the-art in the certification aspects of electric aircraft

At the time of writing this report electric aircraft are flying and commercially available. So the reader may wonder how it is possible for these aircraft to be certified. First it is important to mention these electric aircraft are certified under CS-LSA, the certification specification for Light Sport Aircraft. The CS-LSA has been made suitable for electric propulsion through the following Special Conditions:

- ☐ SC-LSA-F2480-01 LSA propulsion lithium batteries
- ☐ SC-LSA-15-01 Electric powerplant installation for LSA aeroplanes
- ☐ SC-ELA.2015-01 Lithium battery installations

These special conditions can become part of the certification basis for an aircraft type. The certification basis is the total set of requirement to which compliance shall be shown.

SC-LSA-F2480-01 LSA propulsion lithium batteries

Contains considerations for the design and installation of propulsion lithium batteries, as the regular CS-LSA does not cover this sufficiently according to the EASA

Interesting points:

- ☐ Acceptable standard for qualification of the propulsion lithium battery: RTCA DO-311
- ☐ Effect on the battery of the propulsion system in windmilling condition should be taken into account
- ☐ Failure modes shall be identified: High focus on thermal runaway | Protection against overcharging and critical discharge
- ☐ Usable energy to be quantified

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Useful Standards: EN ISO 7010, ASTM F2840 (incorrectly written as F2480 in this SC), ASTM F2245, RTCA DO-311

SC-LSA-15-01 Electric powerplant installation for LSA aeroplanes

- □ Refers to CS-LSA am. 1 and to ASTM F2245-12d which is the Standard Specification for Design and Performance of a Light Sport Airplane
- □ Contains clarifications of ASTM F2245-12d, as well as an indication of which paragraphs of the ASTM standard do not apply
- □ Also refers to ASTM F2840

SC-ELA.2015-01 Lithium battery installations

"This special condition covers the installation of new technology type battery as storage battery in sailplanes, powered sailplanes, light sport aeroplanes or very light aeroplanes, except batteries used for electrical or hybrid propulsion."

Useful Standards: RTCA DO 311, DO 347, UL 1642, UL 2054

CS-25 large transport aircraft

For large transport category aircraft the possible certification basis has not yet progressed to this point. Currently, CS-25 is only valid for turbine engines. This means no existing certification basis can be used to certify a 50 seater hybrid electric aircraft. EWIS (Electrical Wiring Interconnection System) requirements are not specific to low or high voltage, so can be considered applicable to (hybrid-) electric aircraft.

Powerplant certification is normally done against CS-E (currently at amendment 6), which considers piston and turbine engines. It may be assumed that these are approximately valid for (hybrid-) electric powerplants as well. However, no acceptable means of compliance for (hybrid-) electric powerplants currently exits. Certification of a (hybrid-) electric powerplant against CS-E is possible but will most likely require special conditions, CRIs or equivalent safety findings. A CRI is a certification review item, it is a discussion point with EASA regarding the modification of an existing requirement.

In future a special condition for electric and hybrid propulsion systems may arrive. Currently, EASA is working on a Special Condition for Electric & Hybrid Propulsion System (SC-EHPS). The scope of this SC does not include propellers/rotors nor powerplant requirements (as they are at aircraft level) and CS-25 aircraft.

In line with certification of the Pipistrel Velis Electro against CS-LSA and accompanying special conditions, we can expect at least special conditions for Electric propulsion system and the Energy storage.

7.5 Certification aspects during design of the FUTPRINT50 aircraft

Best practice is to design against requirements. The complete set of requirements are derived from an initial set of top level aircraft requirements. Part of the complete set of requirements is the set derived from airworthiness requirements. As discussed this set forms the certification basis and agreement on the set with EASA is obligated. The development and design of the aircraft follows the V-model as indicated in Figure 7.2.

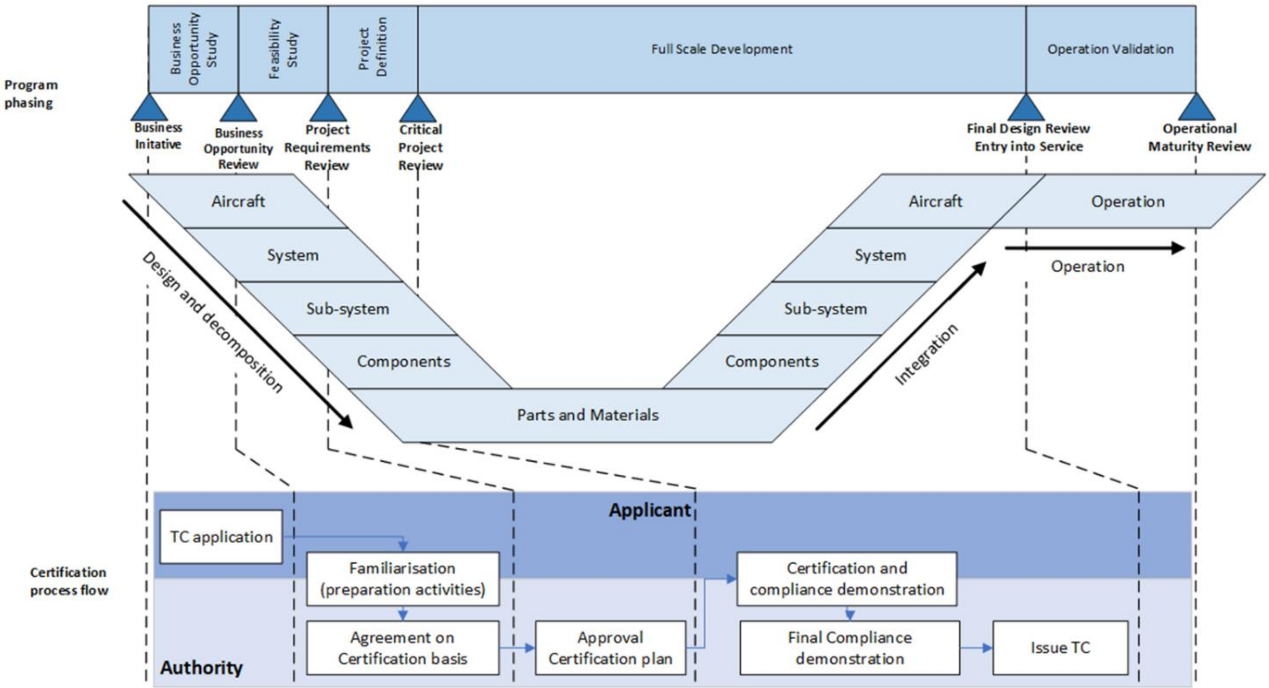
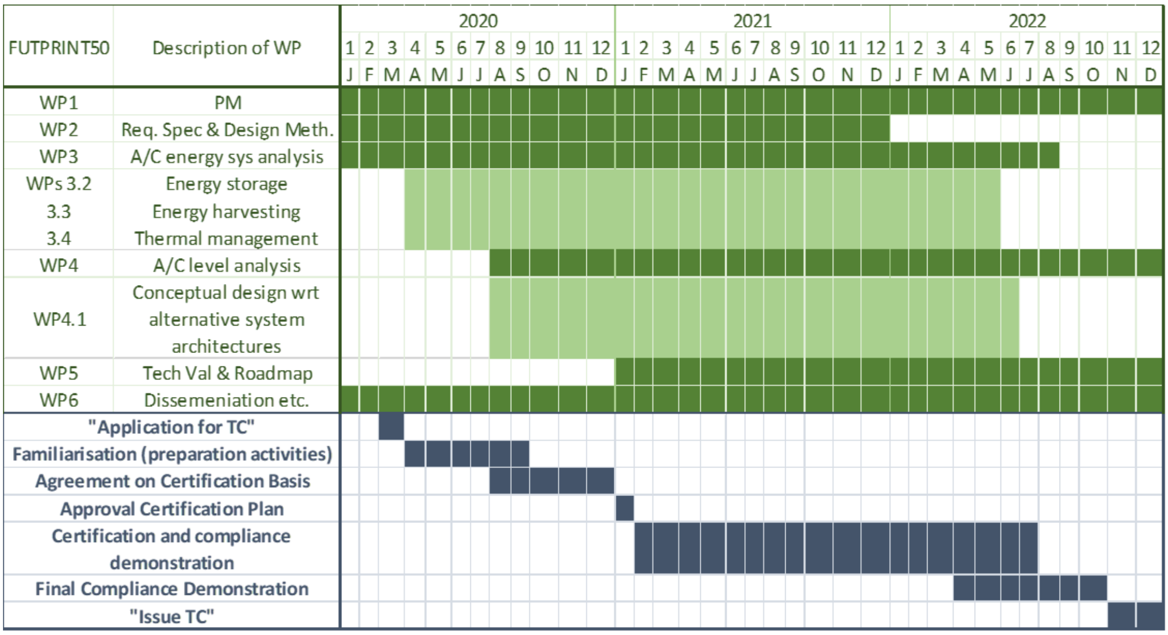


Figure 7.2: Aircraft design and development

A fictional agreement on the certification basis is critical for the advancement of the TRL for hybrid electric flight. This will ensure that the project develops technologies that one day may be deemed airworthy.

7.6 Certification roadmap

Based on the points discussed in this chapter a roadmap for certification has been established. This roadmap depicts the certification activities required for the accompanying design steps in the FUTPRINT50 project. A discussion on the fidelity and scope on the certification activities has yet to be decided upon by the consortium.



FUTPRINT50	Description of WP	2020												2021												2022											
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
WP1	PM	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
WP2	Req. Spec & Design Meth.	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
WP3	A/C energy sys analysis	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
WPs 3.2	Energy storage				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
3.3	Energy harvesting				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
3.4	Thermal management				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
WP4	A/C level analysis								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
WP4.1	Conceptual design wrt alternative system architectures								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
WP5	Tech Val & Roadmap													🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
WP6	Dissemeniation etc.	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
"Application for TC"				■																																	
Familiarisation (preparation activities)					■	■	■	■	■	■																											
Agreement on Certification Basis									■	■	■	■	■																								
Approval Certification Plan														■																							
Certification and compliance demonstration															■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
Final Compliance Demonstration																														■	■	■	■	■	■	■		
"Issue TC"																																				■	■

Figure 7.3: Project roadmap

1 Energy Harvesting – Introduction

Energy harvesting is defined as capturing minute amounts of energy from surrounding energy sources, accumulating and storing them for later use.

It is possible to split these systems into two main categories:

- **Micro-energy harvesting systems** are focused on the alternatives of the conventional battery. These solution can generate mW or μW level power.
- **Macro-energy harvesting** implants based on renewable energy source can generate power of the order of kW or MW.

Energy harvesting from renewable sources can enhance endurance and range performances, increase safety and decrease carbon emission . The typical systems involve

- **solar energy harvesting** by using photovoltaic panels on the wings and fuselage
- **piezoelectric generators** that exploit the naturally occurring vibrations caused by the propeller and by turbulence

Another interesting solution is to use propeller as an aerogenerator in order to recover the energy during the braking phase.

1.2.1.1 Regenerative braking with propellers

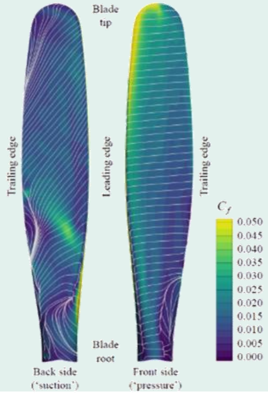
Brief description

- Convert kinetic and potential energy into electrical energy during descent through propeller/electric-motor combo in ‘controlled windmilling’ state [1,2]
- Low pitch setting or low RPM required to enter regenerative regime [4,5]
- Blade loading reverses in regenerative conditions compared to propulsive conditions (drag and power generation, instead of thrust and power consumption) [2,4,5]
- Opportunity for reduced community noise during approach/landing through steeper descent trajectory [6]
- Impact on propeller noise emissions unknown
- Impact on propeller installation effects mostly unknown

Technical data

- Pipistrel showed 17% increase in energy efficiency for small electric trainer aircraft [3]
- Experimental research at TUD shows aerodynamic effiency of about 10% in regenerative mode, low compared to wind turbines (40-50%) [4,5]
- Efficiency decreases with increasing angle of attack for non-optimized propeller design [5]
- Blade loading distribution suboptimal in regenerative conditions for propellers optimized for propulsive conditions [4,5]
- Fraction of mission energy that can be recovered varies strongly with cruise distance and altitude

Pretty pictures



Credit: Pipistrel. AIAA 2018-3206

Synergy/integration challenges

- Reduced noise during descent through steeper descent profiles
- Possible replacement for spoilers/airbrakes (weight, complexity, noise)
- Reduced mission energy consumption (to be used for electric taxi and assisted take-off?)
- Improved landing performance (and reduced brake wear)
- High, time-varying power input during regeneration
- Two-way current from batteries to motor/generator

References

[1] MacCready, P. B., “Regenerative Battery-Augmented Soaring,” Technical Soaring, Vol. 23, No. 1, 1999, pp. 28-32.

[2] Barnes, J. P., “Regenerative Electric Flight: Synergy and Integration of Dual-Role Machines,” 53rd AIAA Aerospace Sciences Meeting, AIAA Paper 2015-1302, Jan. 2015.

[3] Eržen, D., Andrejašič, M., Lapuh, R., Tomažič, J., Gorup, Č., and Kosel, T., “An Optimal Propeller Design for In-Flight Power Recuperation on an Electric Aircraft,” AIAA Paper 2018-3206, June 2018.

[4] Sinnige, T., Stokkermans, T. C. A., van Arnhem, N., Veldhuis, L. L. M., “Aerodynamic Performance of a Wingtip-Mounted Tractor Propeller Configuration in Windmilling and Energy-Harvesting Conditions,” AIAA paper 2019-3033, June 2019

[5] Sinnige, T. et al., “Aerodynamic Analysis of Propellers in Propulsive and Regenerative Conditions”, AVIATION 2020, June 2020.

[6] Thomas, J. L., Hansman, R. J., “Community Noise Reduction Assessment of Using Windmilling Drag on Approach by Hybrid Electric Aircraft,” AVIATION 2020, AIAA Paper 2020-2877, June 2020

1.2.1.1 Regenerative braking with propellers

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	**[1-3]**	[4-6]	**>7**	*Operational on Pipistrel AC (high TRL), BUT (low TRL)..* **) no consideration of integration effects critical for larger aircraft* **) no understanding of acoustic emissions* **) no optimal design approach*
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%**	*Combination of proven technology used in novel way. Consideration of integration effects in FUTPRINT50 to advance state-of-the-art and prepare for higher TRL level in coming years.*
Design tools Maturity TODAY	**In house academy**	General Available	Commercial	*Propeller design routines for conflicting requirements (efficiency vs noise, propulsive vs regenerative) non-existent*
A/C level impact : integration synergy potential			**X**	*See previous slide (propulsion system, batteries, thermal management)*
Regulatory Status Readiness / Maturity TODAY	No or just working groups	**GA or CS23**	Special Condition CS23 / CS 25	*In use on Pipistrel CS23 aircraft*
Consortium Experience TODAY	**X**		**X**	*Propeller aerodynamics and noise: high* *Regenerative propellers: first pilot tests performed at TUD*
Maturity for circular economy / Life Cycle @ EIS				
Potential for diminishing emissions	Low / Indirect	Direct	**High**	*Potential reduction in energy consumption* *Reduction in community noise due to steeper descents*
Operations impact	No change	**Medium**	Paradigm Shift	*Descent phase needs to be revisited, including certification*
Complexity	No change / **Minor Increase**	Medium Increase	High Increase	*Electric propulsion architecture should contain necessary ingredients for regeneration, except additional safety systems for the battery*
Price Point	No change / **Minor Increase**	Medium Increase	High Increase	*Little additional complexity (see previous row)*

1.2.1.2 Regenerative Braking with Landing Gears based motors

Brief Description:

- Convert kinetic energy to a useful form while braking
- Store recovered energy in a battery, supercapacitors, or a flywheel
- Need to be used in combination with friction braking
- Interesting concept for aircrafts
  - Improved efficiency, reduced engine maintenance, emissions and noise
  - Autonomous aircrafts

Technical Data:

- Succefully implemented in railways and vehicles, but still at research level for aircrafts
- Efficicency about 60-70%
- Electrical Taxiing → first step towards Regeneratibe braking
- 65% of the fuel consumed in taxiing can be saved using electrical braking and taxiing for Boieng B737-700, [2]
- Analyzed effect of regenerative braking on airbus A321, [3]
  - Calculated additional weight of the system to be 800 kg
  - Used real drive cycles to obtain the results
  - Energy density can be calculated from the results to be 1.35 Wh/kg

Pretty Pictures:

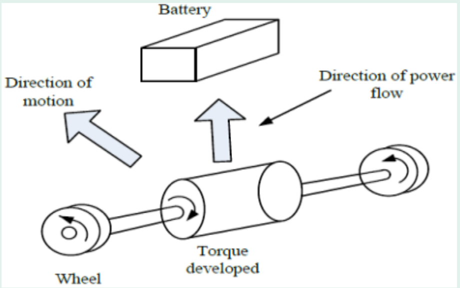


Figure: *Forward driving mode*, [1]

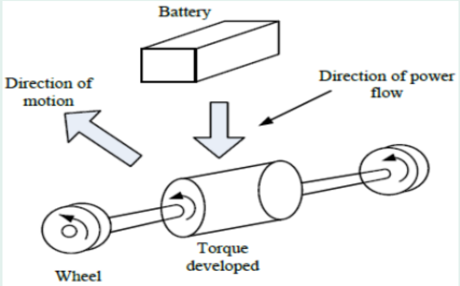


Figure: *Regenerative braking mode*, [1]

Synergy/Integration:

- Design modifiications in landing gears
- Increased weight
- Onboard battery

Refs:

[1] Joseph, Lulu, and K. S. Sreerag. "A Novel Energy Regeneration Technique in Brushless DC Motor for Electric Vehicles.“

[2] Grigore-Müler, Octavian, and Mihai Barbelian. "Regenerative braking for aircraft landing roll phase using an electric machine." 2012 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM). IEEE, 2012.

[3] Heinrich, Maximilian TE, et al. "Regenerative braking capability analysis of an electric taxiing system for a single aisle midsize aircraft." IEEE Transactions on Transportation Electrification 1.3 (2015): 298-307.

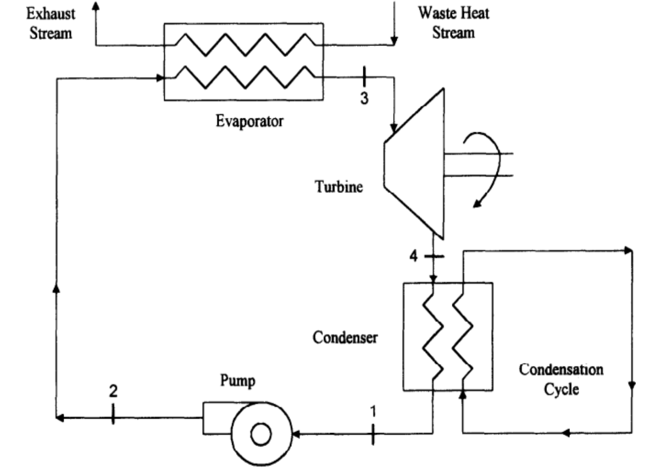
1.2.1.2 Regenerative Braking with Landing Gears based motors

Quick Assesestment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY		4		Operational for cars, railways
Probability of Technology Readiness Level 6/7 in 2030			50%	Electrical taxiing already in process for certification,
Design tools Maturity	In house academy			
A/C level impact : integration synergy potential	High			Landing gears
Regulatory Status Readiness / Maturity	No			
Life cycle	Can last longer than friction braking (exact number unknown)			
Maturity for circular economy (eg, recycle? re-use)	unknown			
Potential for diminishing emissions		Direct		Emissions and noise on airports
Operations impact			Paradigm Shift	Especially taxiing operations

1.2.2 Waste Heat Recovery Systems – Rankine Cycle/Brayton Cycle

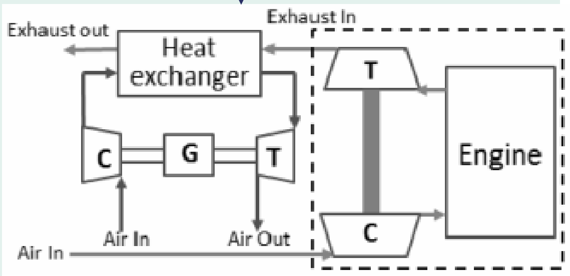
Brief Description

- 60-70% of fuel energy lost as waste heat
- Main cycles to convert waste heat into useful work: Organic Rankine cycle, and Brayton cycle
- Rankine cycle: closed-loop cycle; Brayton cycle: open-loop cycle
- Rankine cycles are found to be most efficient in the literature
- Can work with exhaust temperature as low as 320 K; max temperature can go upto 500 K



← Rankine cycle

Brayton cycle ↓



Technical data

- Very important to choose correct working fluid according to exhaust temperature range
- Expander design is chosen based on the power output and expected pressure ratio
- Thermal efficiency varies from 7-50% depending upon desing and working conditions
- 12-15% saving s in fuel have been reported when applied to vehicles
- Fuel Saving of 1-2% predicted when applied on aircrafts in ECS*

Synergy/Integration

- Integration in the engine/ECS*
- Modification in the bleed air system

Refs

[1] Hung, Tzu-Chen, T. Y. Shai, and S. Kong Wang. "A review of organic Rankine cycles (ORCs) for the recovery of low-grade waste heat." Energy 22.7 (1997): 661-667.

[2] Song, Binyang, et al. "An investigation on the performance of a Brayton cycle waste heat recovery system for turbocharged diesel engines." Journal of Mechanical Science and Technology 27.6 (2013): 1721-1729.

* Environemental Control System

1.2.2 Waste Heat Recovery Systems – Rankine Cycle/Brayton Cycle

Quick Assesestment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY		6		Tested on vehicles
Probability of Technology Readiness Level 6/7 in 2030			50%	No big parties interested
Design tools Maturity			Commercial	
A/C level impact : integration synergy potential			✓	Engine/ECS
Regulatory Status Readiness / Maturity	unknown			
Life cycle			20-25 years	
Maturity for circular economy (eg, recycle? re-use)	✓			
Potential for diminishing emissions			High	Exhaust emissions – CO_2,Nox etc.
Operations impact			Paradigm Shift	

1.3.2 Thermoelectric Generators – Low power applications

Brief description

- Converts temperature gradients into electric power using **Seebeck effect** -

$$V_{seebeck} \propto \Delta \mathrm{T}$$

- Proportanility coefficient depends upon temperature as well as material transport properties (thermal conducitivity and electrical conductivity)
- Fairly compact, solid state, silent operation, low maintenance
- Lifecylce of about 5 years, use of lead and tellurium, so might be difficult to dispose
- Reported power density is greater than 250 W/L and 80 W/kg with $\Delta T_{max} = 120\ {}^{0}C$ [1], another research reports 5.26 W/cm^2 with $\Delta T = 500\ {}^{0}C$ [2]

Technical data

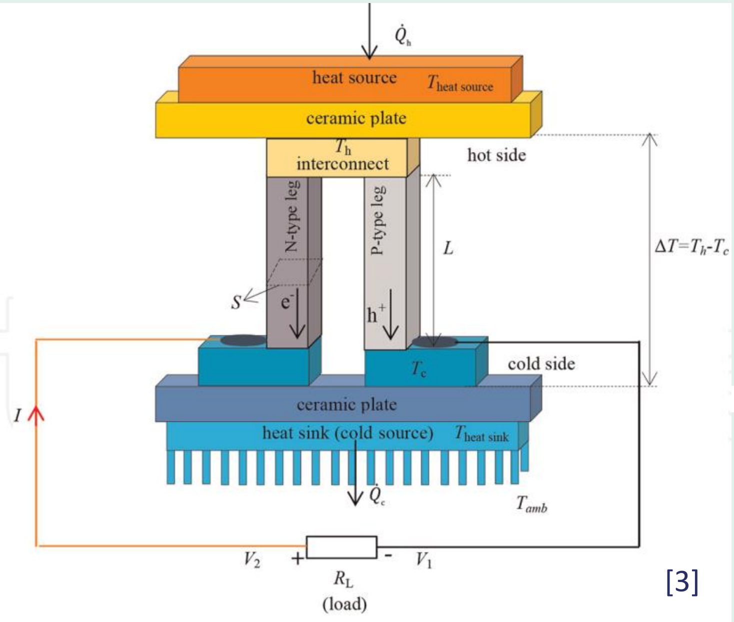
- Power can vary from nW to mW
- Generally low efficiency (<10%)

$$\eta_{max} = \frac{\sqrt{1+ZT}\ -1}{\sqrt{1+ZT}+\frac{T_c}{T_h}} \cdot \frac{\Delta T}{T_h}$$

ZT is called figure of merit, maximum value of ZT is 2 for the current materials

- Current research focused on improving the thermoelectric materials to increase efficiency and to decreases the thermal resistance between heat source and hot side of TEG, similarly between sink and cold side of TEG

Pretty Pictures



[3]

Synergy/Integration

- Fairly light weight
- No direct effect on aircraft design

Refs:

[1] Crane, D. T., et al. "Performance results of a high-power-density thermoelectric generator: beyond the couple." Journal of electronic materials 38.7 (2009): 1375-1381.

[2] Zhang, Yanliang, et al. "High-temperature and high-power-density nanostructured thermoelectric generator for automotive waste heat recovery." Energy Conversion and Management 105 (2015): 946-950.

[3] Enescu, Diana. "Thermoelectric Energy Harvesting: Basic Principles and Applications." *Green Energy Advances*. IntechOpen, 2019.

1.3.2 Thermoelectric Generators – Low power applications

Quick Assesestment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY		6		Already tested on real flights
Probability of Technology Readiness Level 6/7 in 2030			70%	Increasing interest in TEG
Design tools Maturity			Commercial	
A/C level impact : integration synergy potential	low			cabin
Regulatory Status Readiness / Maturity	unknown			
Life cycle		5 years		
Maturity for circular economy (eg, recycle? re-use)		At research level		
Potential for diminishing emissions	Low/Indirect			Replace wired sensors with wireless systems
Operations impact	No change			

1.3.2 Thermionic Generator (TIG)

Brief Description

- Idea first proposed by Schlichter in 1915
- Converts thermal energy directly into electrical energy using thermionic emission
- Considered more efficient compared to thermoelectric generators
- Low work function materials are required to achieve high efficiency
- Research focused on techniques - advance coating, intercalation, surface nanostructuring etc.
- Space charge effect arises the need to use technologies – reduced interelectrode gap, positive compensation, external electric and magnetic fields etc.

Pictures

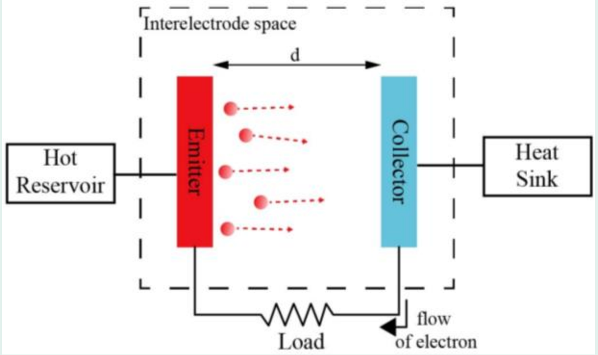


Figure: *Schematic of a TIG*, [1]

Technical Data

- Power density of 32 W/cm2 for temperatures > 1000 °C
- Power density rapidly decreases below 1000 °C
- 15% efficient with electrodes between 570 °C and 1300 °C
- Theoretical efficiency close to Carnot efficiency
- For high efficiency, low work function electrodes and high temperature heat source are required

Benefits/Synergies

- Compact
- Higher power density than TEG*
- Silent Operation
- Long life span
- Can use exhaust energy of the engine

Drawbacks

- Needs high temperature heat source
- Modifications needed in the engine design
- Still in the research phase for aircraft

* Thermoelectric Generator.

1.3.2 Thermionic Generator (TIG)

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY		4		Has been used in space applications, but no instance of usage in aircraft
Probability of Technology Readiness Level 6/7 in 2030	< 60%			Some companies like Space Charge LLC are working on it but as a main source of power
Design tools Maturity TODAY	In house academy			Few mathematical models
A/C level impact : integration synergy potential		medium		Engine
Regulatory Status Readiness / Maturity TODAY	No or just working groups			
Consortium Experience TODAY	??			What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS	unknown			Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect			Canbe used for low power applications
Operations impact		Medium		
Complexity			High Increase	Modifications in engine design
Price Point			High Increase	Specilized material required with lowe work function along with vaccum sealing

1.3.2 Thermionic Generator (TIG)

[1] Khalid, Kamarul Aizat Abdul, Thye Jien Leong, and Khairudin Mohamed. "Review on thermionic energy converters." IEEE transactions on electron devices 63.6 (2016): 2231-2241.

[2] Zabek, D., and F. Morini. "Solid state generators and energy harvesters for waste heat recovery and thermal energy harvesting." Thermal Science and Engineering Progress 9 (2019): 235-247.

[3] Kodihal, K., and A. Sagar. "A review on opportunities of thermionic regeneration system in hybrid electric vehicle." Journal of Physics: Conference Series. Vol. 1230. No. 1. IOP Publishing, 2019

[4] Xuan, X. C., and D. Li. "Optimization of a combined thermionic–thermoelectric generator." Journal of Power Sources 115.1 (2003): 167-170.

(More exhaustive references can be found in the energy harvesting review report)

1.3.3 Electro-mechanical/Electro-hydrostatic Actuator

Brief Description

- Three types of PBW: Electro-mechanical actuation (EMA), Electro-hydrostatic actuation (EHA), and Integrated Actuator Package
- Retains all the advantages of FBW along with additional ones: Lighter in weight, Fault tolerant, Reduced maintenance cost, etc.
- Electric actuators regenerate energy when surfaces are decelerated
- Conventionally, regenerated energy is dissipated as heat using shunt
- Store the regenerated energy instead of dissipating for future use

Pictures

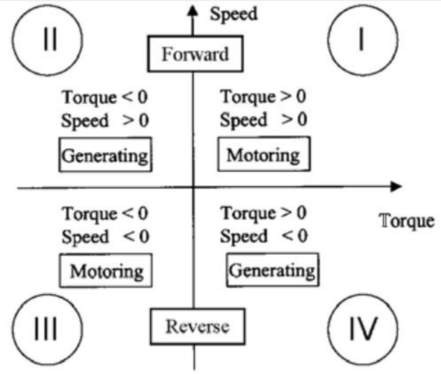


Figure: *Four-quadrant operation of the surface control actuators,* [1]

Technical Data

- Eight different architectures to manage regenerated power
- Centralized energy storage with a shunt as backup is the optimum configuration
- Lot of research focused on using regenerated power in actuators: Induction generator based auxiliary power unit, Load regeneration back to distribution bus, Two stage matrix converter
- Two power management strategies: load-leveling and load-following
- Different architectures to manage power as given in slide 5
- Regenerated model for EMA tested for real flight profile,[2]: Mean and peak power reported to be 1.93 W and 260 W, Peak energy produced is 40 J in 0.3 s

Benefits/Synergies

- Reduced weight of actuators
- Elimination of resistors and related cooling equipment
- Increased efficiency due to regenerated energy

Drawbacks

- Modifications in power bus
- Energy storage device required to store energy

1.3.3 Electro-mechanical/Electro-hydrostatic Actuator

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY		[4-6]	>7	Already implemented in Commercial aircraft
Probability of Technology Readiness Level 6/7 in 2030			> 65%	
Design tools Maturity TODAY			Commercial	
A/C level impact : integration synergy potential		medium		Elimination of heavy resistors in actuators and related cooling equipment
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY	??			What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS	unknown			
Potential for diminishing emissions	Low / Indirect			Use regenerated power and reduce stress on thermal management
Operations impact	No change			
Complexity	Minor Increase			Replace shunt with Energy storage
Price Point	Minor Increase			Few or no additional components required

1.3.3 Electro-mechanical/Electro-hydrostatic Actuator

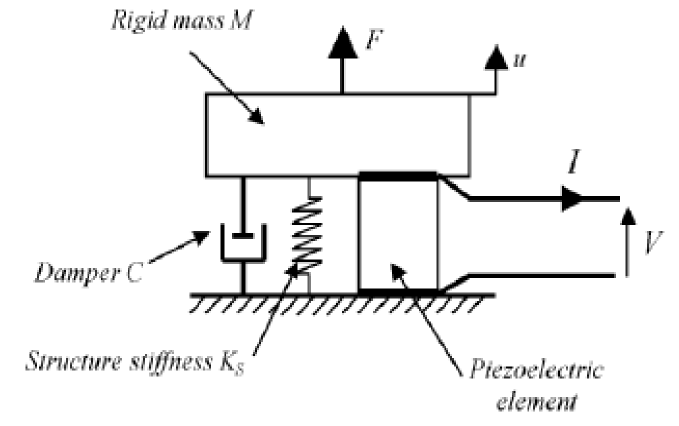
Reference

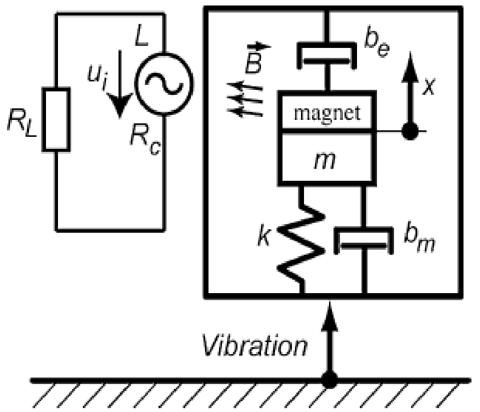
1. Ganev, Evgeni, and Bulent Sarlioglu. Improving load regeneration capability of an aircraft. No. 2009-01-3189. SAE Technical Paper, 2009.
2. Trentin, A., et al. "Power flow analysis in electro-mechanical actuators for civil aircraft." IET Electric Power Applications 5.1 (2011): 48-58.
3. G. Qiao, G. Liu, Z. Shi, Y. Wang, S. Ma, and T. C. Lim,A review of electromechanical actuators formore/all electric aircraft systems,Proceedings of the Institution of Mechanical Engineers, PartC: Journal of Mechanical Engineering Science232, 4128 (2018).
4. N. Alle, S. S. Hiremath, S. Makaram, K. Subramaniam, and A. Talukdar,Review on electro hy-drostatic actuator for flight control,International Journal of Fluid Power17, 125 (2016).
5. C. I. Hill, S. Bozhko, T. Yang, P. Giangrande, and C. Gerada,More electric aircraft electro-mechanical actuator regenerated power management,in2015 IEEE 24th International Symposium on Industrial Electronics (ISIE)(IEEE, 2015) pp. 337–342.
6. D. Margolis,Energy regenerative actuator for motion control with application to fluid powersystems,(2005).
7. Y. Deng, S. Y. Foo, and I. Bhattacharya,Regenerative electric power for more electric aircraft,inIEEE SOUTHEASTCON 2014(IEEE, 2014) pp. 1–5.
8. P. Wheeler, J. Clare, S. Bozhko, and A. Kulshreshtha,Regeneration in aircraft electrical powersystems?, Tech. Rep. (SAE Technical Paper, 2008).
9. T. X. Wu, J. Zumberge, and M. Wolff,On regenerative power management in more electric air-craft (MEA) power system,inProceedings of the 2011 IEEE National Aerospace and ElectronicsConference (NAECON)(IEEE, 2011) pp. 211–214.
10. D. Van Den Bossche,The A380 flight control electrohydrostatic actuators, achievements andlessons learnt,in25th international congress of the aeronautical sciences(2006) pp. 1–8.

1.3.4 Energy harvesting: Piezoelectric

Brief Description

Energy harvesting is defined as capturing minute amounts of energy from one or more of the surrounding energy sources, accumulating and storing them for later use. One of the most studied solution involves the use of piezo-electric material, which can convert mechanical vibration into electrical energy with very simple structure.





Technical Data

Piezoelectricity represents pressure electricity and is a property of certain crystalline materials such as quartz, Rochelle salt, tourmaline, and barium titanate that develop electricity when pressure is applied, this is called the direct effect and it can be used as a sensor or energy transducer.

The commonly used piezoelectric energy harvester configuration is a cantilevered beam with one or two piezoceramic layer. The L-shaped structure can be tuned to have the first two natural frequencies much closer to each other (on the frequency axis) when compared to the conventional cantilevered beam case. Such effect is a favorable feature in the sense of broadband energy harvesting for random or varying-frequency excitations.

Benefits/Synergies

- piezo-electric material can convert mechanical vibration into electrical energy with very simple structure.
- the exploitation of naturally occurring vibrations caused by the propeller and by turbulence through piezoelectric generators.
- The typical systems involve solar energy harvesting by exploiting photovoltaic panels on the wings and fuselage.

Drawbacks

- A limitation is that the obtained electrical energy from vibration is small, rectification and energy storing circuits should be able to activate in such a low power condition.

1.3.4 Energy harvesting: Piezoelectric

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6]	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65%	Why?
Design tools Maturity TODAY	In house academy	General Available	Commercial	
A/C level impact : integration synergy potential				(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Which emissions?
Operations impact	No change	Medium	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase	High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase	High Increase	Why? What material needed? Etc.

1.3.4 References

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- Sliwinski, J., Gardi, A., Marino, M., & Sabatini, R. (2017a). Hybrid-electric propulsion integration in unmanned aircraft. *Energy*, *140*, 1407–1416.
- Magoteaux, K. C., Sanders, B., & Sodano, H. A. (2008). Investigation of an energy harvesting small unmanned air vehicle. *Active and Passive Smart Structures and Integrated Systems 2008*, *6928*, 692823. https://doi.org/10.1117/12.775851
- Erturk, A., Renno, J. M., & Inman, D. J. (2009). Modeling of piezoelectric energy harvesting from an L-shaped beam-mass structure with an application to UAVs. *Journal of Intelligent Material Systems and Structures*, *20*(5), 529–544. https://doi.org/10.1177/1045389X08098096

1.3.5 Energy Harvesting – Photovoltaic Devices

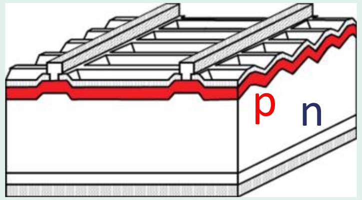
Brief Description

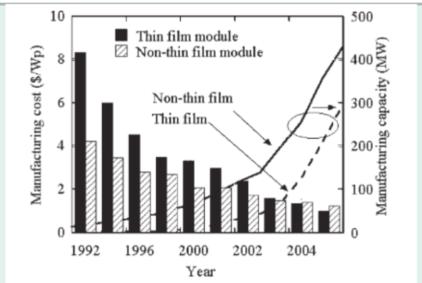
Three principal technologies are known (Silicon Wafers, Thin Film,Multijunction)

- Crystalline silicon wafers is the most investigated technology the reach 25 % efficiency.
- Thin film technologies are comparable in efficiency to Silicon Wafers and use low cost eco-friendly processes (A variety of substrates with different physical and chemical properties and each affects the overall performance of the device)
- Multijunction solar cells are a new technology little known but has efficiencies about 40 % and in the next year will reach 50%.

Pictures

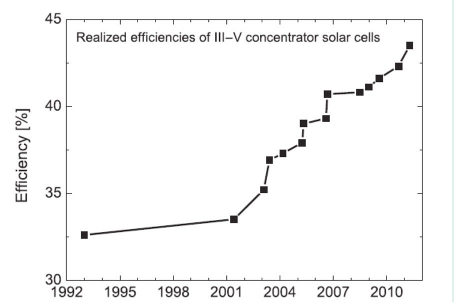
Crystalline Silicon Wafers





Thin Film Tecnologies

Multijunction Solar Cells



Technical Data

- Crystalline Silicon Wafer : They are reliable due to their simple, large area p–n junction design. In order to improve cell efficiency strategies generally are focused on reducing carrier recombination processes.
- Thin Film that uses various substrates with different physical and chemical properties to increase overall efficiency. It has more or less the same efficiency as silicon wafers but is more low-cost and uses eco-friendly processes.
- Multijunction solar Cell which uses many subcells with various semiconductors each one of absorbs a portion of the solar energy spectrum. This allows to do not lose efficiency at high temperatures and increase efficiency which is around 40%

Benefits/Synergies

- Crystalline silicon wafers is the most investigated technology the reach 25 % efficiency
- Thin film technologies are comparable in efficiency to Silicon Wafers and use low cost eco-friendly processes
- Multijunction solar cells are a new technology little known but has efficiencies about 40 % and in the next years will reach 50%

Drawbacks

- For silicon wafers Efficiency decline about 0.5 % per celsius degree and the maximum efficiency is already reached
- Photovoltaic technologies of the second generation (thin film, multijunction) are less investigated but are promising
- New technology face comparable fundamental issues related to the steps involved in the conversion of photon energy into electricity

1.3.5.1 Energy Harvesting – Photovoltaic Devices : Crystalline Silicon Wafers

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6]	>7	
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65%	The maximum efficiency is already reached
Design tools Maturity TODAY	In house academy	General Available	Commercial	
A/C level impact : integration synergy potential				
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	NOx CO CO2
Operations impact	No change	Medium	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase	High Increase	
Price Point	No change / Minor Increase	Medium Increase	High Increase	Silicon

1.3.5.2 Energy Harvesting – Photovoltaic Devices : Thin Film Technologies

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6]	>7	Less investigated
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65%	Photovoltaic of 2nd generation
Design tools Maturity TODAY	In house academy	General Available	Commercial	
A/C level impact : integration synergy potential				(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Nox CO CO2
Operations impact	No change	Medium	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase	High Increase	
Price Point	No change / Minor Increase	Medium Increase	High Increase	

1.3.5.3 Energy Harvesting – Photovoltaic Devices : Multijunction Solar Cells

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6]	>7	Less investigated
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65%	efficiencies in the next years will reach 50%
Design tools Maturity TODAY	In house academy	General Available	Commercial	
A/C level impact : integration synergy potential				(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Nox CO CO2
Operations impact	No change	Medium	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase	High Increase	
Price Point	No change / Minor Increase	Medium Increase	High Increase	Variety of semiconductors

1.3.5 References

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- Mulligan, W. P., Rose, D. H., Cudzinovic, M. J., De Ceuster, D. M., McIntosh, K. R., Smith, D. D., & Swanson, R. M. (2004). Manufacture of solar cells with 21% efficiency. Proc. 19th EPVSEC, 387.
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- Bailey, S., & Raffaelle, R. (2011). Space solar cells and arrays. *Handbook of photovoltaic science and engineering*, 365-401.

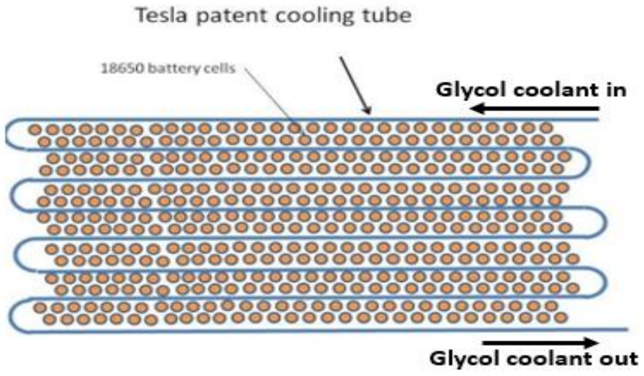
2) Thermal management

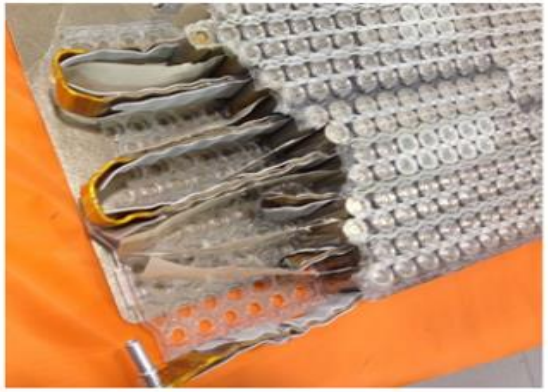
2.4.1 Liquid Cooling Systems

Liquid cooling transfer the heat of mechanical and electronic devices. The cooling fluid can be polysiloxane thermo oil, Ethylene glycol water (EGW), propylene glycol water (PGW), Polyalphaolefin (PAO), Automatic Transmission Fluid (ATF) and others.

A pump pushes the liquid in a closed system of tubes to provide the cooling to the heat source, then the warm fluid passes through a heat exchanger to be cooled using the ambient as heat sink or associated with VCS and skin heat exchangers.

This method increases the effectiveness of the heat transfer because presents higher heat transfer coefficients and heat capacity than air, ensuring a higher dissipation of heat load. The technology has low power consumption and low noise emissions.





- The temperature operation limit depends on the fluid properties;
- May be subjected to the environment heat sink temperature;
- It may need an anti-corrosive fluid;
- The system has equipment with moving parts, such as pump, fan, bowlers, others.

Liquid cooling can be integrated to other aircraft cooling systems such as air cooling, skin heat exchangers and heat pipes / thermosyphons.

Refs:

- SAE AIR1811 - Liquid Cooling Systems
- [JW Chapman et al.] Development of a Thermal Management System for Electrified Aircraft . https://doi.org/10.2514/6.2020-0545
- [Yang et al.] Thermal management of Li-ion battery with liquid metal - https://doi.org/10.1016/j.enconman.2016.03.054
- [A Hoadley et al.] Comparison of immersed liquid and air cooling of NASA's Airborne Information Management System - https://doi.org/10.2514/6.1992-2901

2.4.1 Liquid Cooling Systems

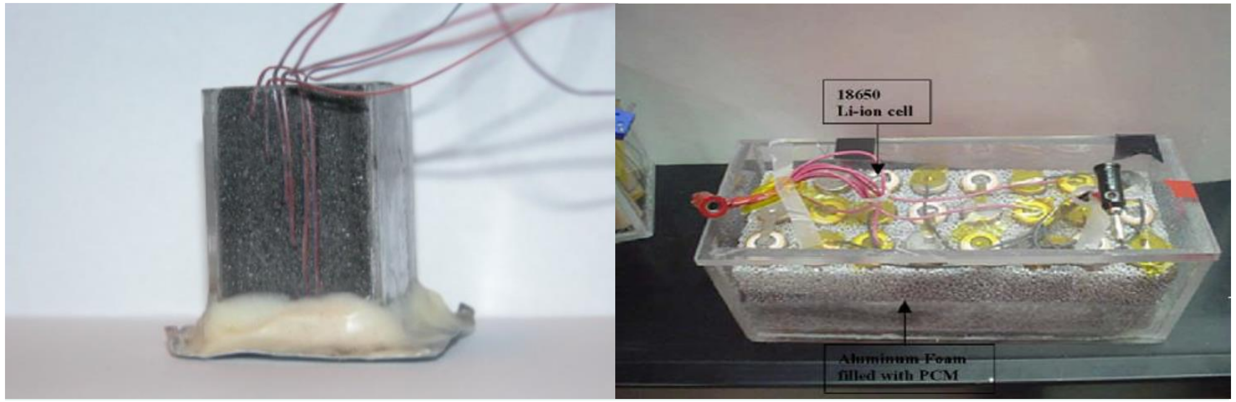
Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TRL) TODAY	[1 – 3]	[4 – 6]	**>7**	The technology is applied in commercial (e.g. B787) and military aircraft.
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%**	The technology is applied in commercial (e.g. B787) and military aircraft.
Design tools Maturity	In house academy	General Available	**Commercial**	The technology is applied in commercial (e.g. B787) and military aircraft.
A/C level impact : integration synergy potential			**High**	Can be integrated to other aircraft systems such as cabin and e-bay air cooling, skin heat exchangers and heat pipes / thermosyphons.
Regulatory Status Readiness / Maturity (TODAY)			**FAA Part 25, EASA CS-25, military.**	The technology is applied in commercial (e.g. B787) and military aircraft.
Consortium Experience TODAY		**Medium**		Designing and sizing lliquid cooling systems, but not integration on aicraft products.
Maturity for circular economy / Life Cycle @ EIS				Unknown.
Potential for diminishing emissions	**Low/Indirect**	Direct	High	Indirect emissions.
Operations impact	No change	**Medium**	Paradigm Shift	Aircraft ground support equipment (GSE) and maintenance tasks aggregate higher costs.
Complexity	**Low**			
Price Point				Unknown.

2.4.2 Thermal Accumulators (e.g. phase change materials)

Phase change materials (PCM) are substances such as graphitized carbon, sodium acetate, water and others, that absorb or release large amounts of heat over a defined temperature range due to the phase transition, from solid to liquid and vice versa.

Using this technology the PCM can provide cooling and heating process to battery, motor or electronic devices, depending on the objective, when the material reaches its specific phase change temperature.

Referred as latent heat storage materials, the PCM are considered highly efficient thermal storage.



- Each kind of PCM have a defined temperature range when the material changes the state or phase;
- The thermo-physical properties should be accurate for the correct objective;
- The PCM will have different solid and liquid phase properties;
- Chemically stable, so the PCM can be in service for a long time and not be dangerous;
- Noncorrosive, nonflammable and safe.

Phase change materials (PCM) can be integrated to other cooling systems such as air cooling, VCS, specially to absorb high heat fluxes during equipment transient conditions.

- [A Fedden et al.] Graphitized Carbon Foam with Phase Change Material for Thermal Energy Storage. https://doi.org/10.2514/6.2006-3133
- [Khateeb at al.] Thermal management of Li-ion battery with phase change material for electric scooters: experimental validation - https://doi.org/10.1016/j.jpowsour.2004.09.033

2.4.2 Thermal Accumulators (e.g. phase change materials)

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TRL) TODAY	[1 – 3]	**[4 – 6]**	>7	Unknown aircraft applications.
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%**	The technology is evolving with researches related to batteries cooling, as example.
Design tools Maturity	In house academy	**General Available**	Commercial	No specific tools designed for aircraft development.
A/C level impact : integration synergy potential	**Low**			Depending on the level of integration, the impacts can be higher. If incorporated in equipment design, impacts are expected to be low.
Regulatory Status Readiness / Maturity (TODAY)	**Low**			Technology is evolving with the objective to be applied in the HEA.
Consortium Experience TODAY	**Low**			Theoretical models. No integration on aircraft products.
Maturity for circular economy / Life Cycle @ EIS				Unknown.
Potential for diminishing emissions	**Low/Indirect**	Direct	High	Indirect emissions.
Operations impact	No change	**Medium**	Paradigm Shift	Aircraft ground support equipment (GSE) and maintenance tasks shall be defined.
Complexity		**Medium**		
Price Point				Unknown.

2.4.3 Cryocooling systems for high temperature superconductor (HTS)

MAI presentation of the Optimal Design Analysis and Methods of the Thermal Menagement R&D of High Temp Superconductor Crio Cooling Systems,, LAB Demonstrator and Tests Results.

For the operation of **High Temperature Superconducting (HTS) components** its necessary to reliably maintain the Temperature Level of the second-generation HTS in the **range of 65 ... 75 K.** The complex integrate R&D Methods was used the Open and Circulating CrioCooling Systems. In the circulation circuits of Criopreservation systems was requirement and used the **Stirling and Gifford McMahon Thermodynamic cycles.**

The Criogenic Cool System was designed with the use of these Thermal Management Cycles to have relatively high efficiency with limited resources. Another approach to the development of **Criosystems** offers the use of Powerful Pulsating Pipes (Q-drive, USA) an Important advantage of pulsating pipes is the almost complete absence of moving parts in them which allows to dramatically increase the reliability of the device and increase the interval between maintenance operations. However they are inferior in **Cooling CrioRefrigerators** on the basis of of Stirling cycle. The most promising are **CrioRefrigerators** using **Turbochargers and Turboexpanders based on the Brighton cycle**.

- **Thermal Management of HTS Criocooling optimal design schemes :**

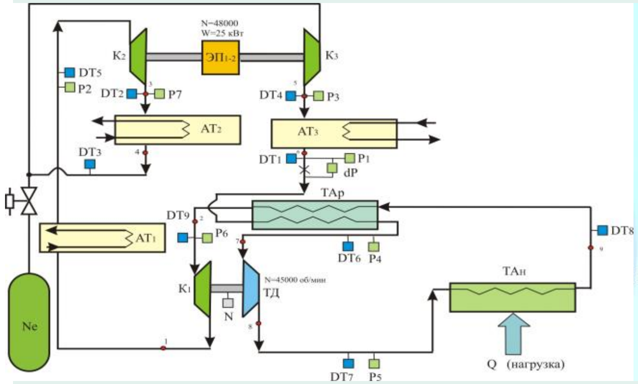
  1. Open cycle 2. Regenerative cycle 3. Recovery cycle

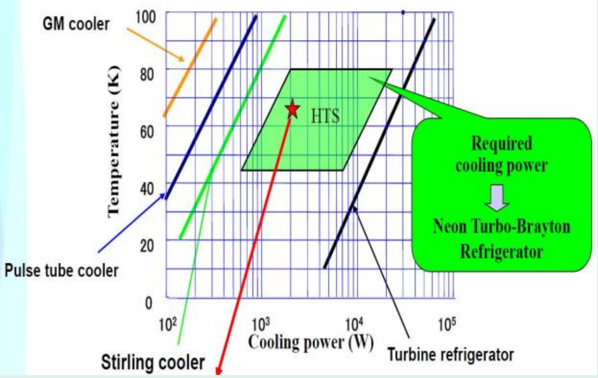
- **Integrate Design Analysis of applied schemes and Comparing of the Thermal Cycles**

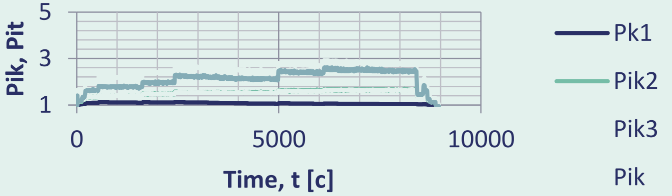
  1. Standard Joule-Thomson cooling cycle 2. Double pressure cycle with cooled by expansion flow

  3. Modified double pressure cycle with cooled by expander flow

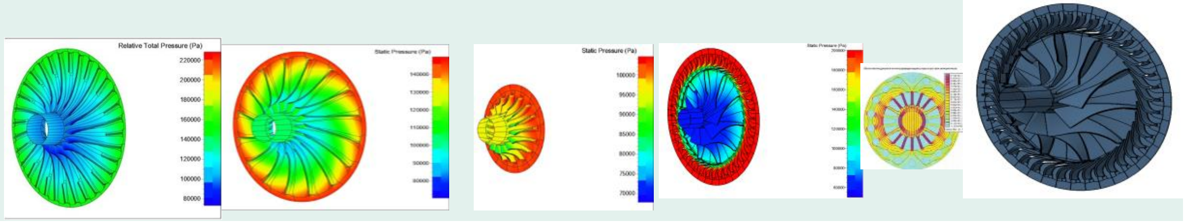
- **Technical appearance and calculation of the characteristics HTS Criocooling system**
- **Mathematical model of the Hybrid Electric Propulsion Criocooling system**
- **Two-stage Neon Electric Compressor and Turbo Expander Components**







Ref.: - MAI Science R&D Report 2018-2019-2020, Moscow, RU;- Conference papers 2018/2019



2.4.3 Cryocooling systems for high temperature superconductor (HTS) (by MAI)

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	**[1 – 3]**	[4 – 6]	>7	Unknown aircraft applications.
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%**	Beased on TRL evolution.
Design tools Maturity	**In house academy**	General Available	Commercial	
A/C level impact : integration synergy potential			**High**	
Regulatory Status Readiness / Maturity (TODAY)	**Low**			Unknown aircraft applications.
Consortium Experience TODAY			**High**	MAI experience in research projects (theoretical models, lab tests, etc.)
Maturity for circular economy / Life Cycle @ EIS				Unknown
Potential for diminishing emissions	**Low/Indirect**	Direct	High	Indirect emissions
Operations impact	No change	**Medium**	Paradigm Shift	Aircraft ground support equipment (GSE) and maintenance tasks to be defined.
Complexity			**High**	
Price Point				Unknown

2.4.4 Pumped two phase systems

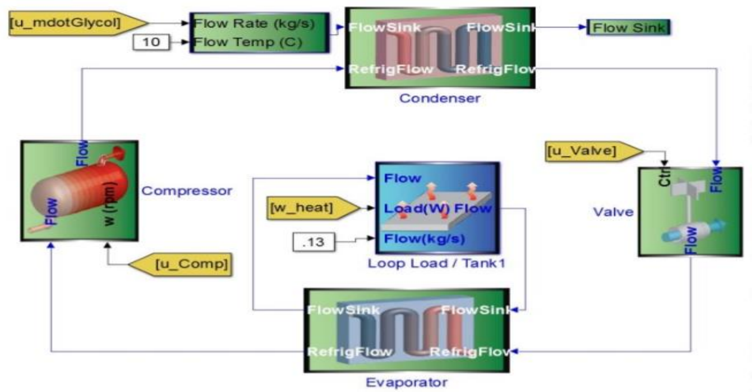
Brief Description

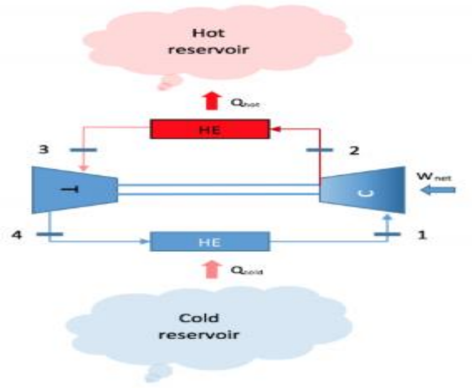
Vapor cycle systems are closed loop systems that circulate refrigerant fluid via tubing, which absorbs and removes heat from a device and rejects to a heat sink. The refrigerant fluid has specific properties under varying pressures and temperatures, and the most common refrigerants are R22, R134a and R410a.

The main processes of vapor cycle systems are: compression of the refrigerant by a compressor, heat rejection of the refrigerant to a condenser, expansion of the fluid through an expansion device (such as a valve), and heat absorption by the refrigerant in an evaporator. The refrigerant fluid is a two-phase vapor-liquid mixture, that have different temperatures and pressures at the condenser and evaporator.

Vapor cycle systems can be integrated to other cooling systems such as liquid cooling loops, air cooling, heat pipes and others.

Pictures





Technical Data

Vapor cycle systems have higher power consumption but can achieve low temperatures to cool electrical components in an aircraft and provide air conditioning to the passengers and crew. Vapor cycle systems provide a much higher coefficient of performance than air cycle systems. This technology allows a broader cooling envelope since the heat is rejected at temperatures below ambient (ex.: external air on ground).

Benefits/Synergies

- High coefficient of performance
- Very mature
- Integrative to other thermal management cycle or system

Drawbacks

- High complexity
- Environmental-unfriendly

- References
- SAE ARP85 - Air Conditioning Systems for Subsonic Airplanes
- [SD Jackson et al.] Control of Vapor Compression Cycles under Transient Thermal Loads. https://doi.org/10.2514/6.2019-0536
- [R Kabir et al.] Investigation of a Cooling System for A Hybrid Airplane https://doi.org/10.2514/6.2018-4991

2.4.4 Pumped two phase systems (e.g. vapor cycle systems, evaporative cooling)

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TRL) TODAY	[1 – 3]	[4 – 6]	**>7**	The technology is applied in commercial and military aircraft.
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%**	The technology is applied in commercial and military aircraft.
Design tools Maturity	In house academy	General Available	**Commercial**	The technology is applied in commercial and military aircraft.
A/C level impact : integration synergy potential			**High**	Can be integrated to other aircraft systems such as cabin and e-bay air cooling, skin heat exchangers, liquid cooling, etc.
Regulatory Status Readiness / Maturity (TODAY)			**FAA Part 25, EASA CS-25, military.**	The technology is applied in commercial and military aircraft.
Consortium Experience TODAY			**High**	Technology integrated on aicraft products (e.g. Embraer Phenom 100).
Maturity for circular economy / Life Cycle @ EIS				Unknown.
Potential for diminishing emissions	**Low/Indirect**	Direct	High	Indirect emissions.
Operations impact	**No change**	Medium	Paradigm Shift	Aircraft ground support equipment (GSE) and maintenance tasks are already known.
Complexity		**Medium**		
Price Point				Unknown.

2.4.5 Air cooling

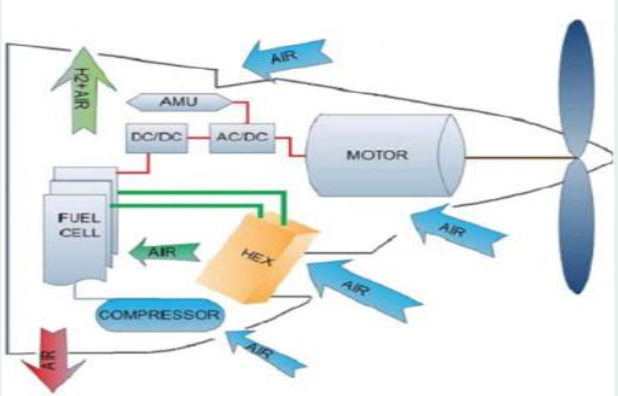
Brief Description

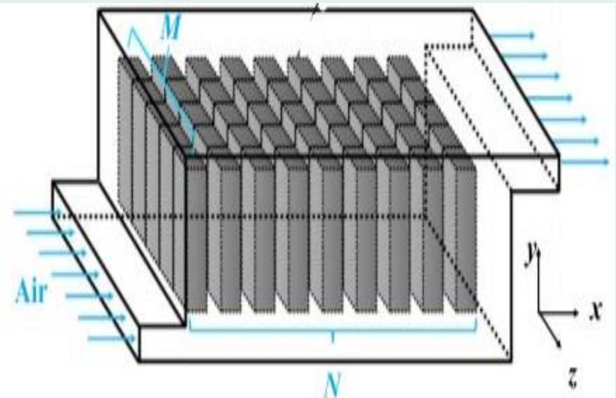
Generally, air cooling is accomplished by flowing air around/inside the heat loads. The air flow can be natural or forced convection. Forced convection is accomplished by fans inside equipment or compartments.

Also, air cycle systems (such as bootstrap systems) are used in order to decrease the cooling air temperature below ambient, through a compression, cooling and expansion cycle. Thereunto, a high-pressure source of air (ex.: air flow bled from engine compressors) is used.

Ram air cooling is achieved at flight by SCOOPs and/or NACAs directing the external airflow to heat exchangers. However, aircraft ground operations are supported by fans. Obs.: ram air temperature is limited by the external air temperature.

Pictures





- Subjected to the environment heat sink temperature;
- Equipment such as fans, blowers and ram air intakes (such as SCOOP or NACA) are needed;
- Shall present high penalties in drag;
- Air cycle machines require high (pneumatic) power consumption.

Benefits/Synergies

- Simplicity
- Very mature
- Air cooling can be integrated to other cooling systems such as liquid cooling loops, vapor cycle systems (VCS), heat pipes and others.

Drawbacks

- Dependent on ambient air temperature
- Increasing aircraft drag

- References
- [Jiaqiang et al.] Effects of the different air cooling strategies on cooling performance of a lithium-ion battery module with baffle - https://doi.org/10.1016/j.applthermaleng.2018.08.064.
- [RJ Christie] Cooling of Electric Motors Used for Propulsion on SCEPTOR – NASA/TM – 2017-219134
- [Kai Chen et all.] Design of the structure of battery pack in parallel air-cooled battery thermal management system for cooling efficiency improvement. https://doi.org/10.1016/j.ijheatmasstransfer.2018.12.024
- [G. Romeo et al.] Engineering Method for Air-Cooling Design of Two-Seat Propeller-Driven Aircraft Powered by Fuel Cells. https://doi.org/10.1061/(ASCE)AS.1943-5525.0000055

2.4.5 Air cooling (e.g., fans, air cycle machines, ram air)

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TRL) TODAY	[1 – 3]	[4 – 6]	**>7**	The technology is applied in commercial and military aircraft.
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%**	The technology is applied in commercial and military aircraft.
Design tools Maturity	In house academy	General Available	**Commercial**	The technology is applied in commercial and military aircraft.
A/C level impact : integration synergy potential			**High**	Can be integrated to other aircraft systems such as cabin and e-bay air cooling, skin heat exchangers, liquid cooling, etc.
Regulatory Status Readiness / Maturity (TODAY)			**FAA Part 25, EASA CS-25, military.**	The technology is applied in commercial and military aircraft.
Consortium Experience TODAY			**High**	Technology integrated on aicraft products (e.g. Embraer 170/190 family, Embraer E2 family, Embraer Legacy, etc.).
Maturity for circular economy / Life Cycle @ EIS				Unknown.
Potential for diminishing emissions	**Low/Indirect**	Direct	High	Indirect emissions.
Operations impact	**No change**	Medium	Paradigm Shift	Aircraft ground support equipment (GSE) and maintenance tasks are already known.
Complexity	**Low**			
Price Point				Unknown.

2.4.6 Skin heat exchangers

Brief Description

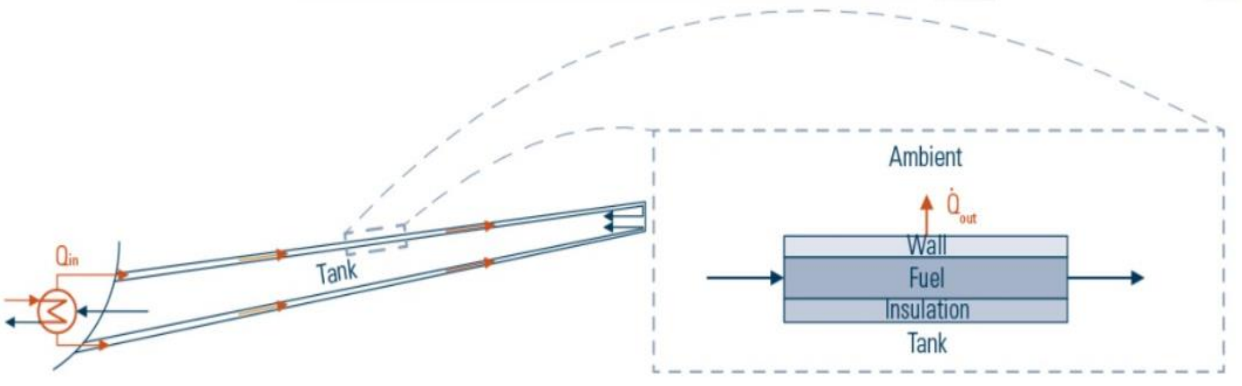
The aircraft skin act as a heat exchanger transferring heat to the ambient air. Skin heat exchangers (SHX) can be used mainly at flight conditions when the external air presents adequate heat transfer properties.

SHX can be constructed by fuselage and/or wing panels that circulate the heat transfer fluid (liquid or air) through internal channels.

The SHX can be part of a cooling system as an alternative or complement of ram air heat exchangers.

Skin heat exchanger can be integrated to other cooling systems such as liquid cooling loops, air cooling, heat pipes and others.

Pictures



- Subjected to the environment heat sink temperature;
- There is no penalty of additional drag;
- This technology requires considerations of heat rejection through the aircraft skin, such as external convection (heat transfer coefficient), temperature and area.

Benefits/Synergies

- High efficiency
- Simple
- Synergy

Drawbacks

- Dependent on ambient temperature
- Needed additional pumps energy

- [[Julie Schneider et al.] Aircraft Skin-Cooling Airflow Distribution. https://doi.org/10.2514/2.6429
- [H Kellermann et al.] Assessment of fuel as alternative heat sink for future aircraft. https://doi.org/10.1016/j.applthermaleng.2020.114985
- [Bauhaus Luftfahrt] Fuel as Alternative Heat Sink for Future Aircraft. <https://www.bauhaus-luftfahrt.net/en/research/systems-aircraft-technologies/fuel-as-alternative-heat-sink-for-future-aircraft/>

2.4.6 Skin heat exchangers

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TRL) TODAY	[1 – 3]	[4 – 6]	**>7**	The technology is applied in commercial (e.g. A320) and military aircraft.
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%**	The technology is applied in commercial (e.g. A320) and military aircraft.
Design tools Maturity	In house academy	General Available	**Commercial**	The technology is applied in commercial (e.g. A320) and military aircraft.
A/C level impact : integration synergy potential			**High**	Can be integrated to other aircraft cooling systems such as cabin and e-bay air cooling, liquid cooling, VCS.
Regulatory Status Readiness / Maturity (TODAY)			**FAA Part 25, EASA CS-25, military.**	The technology is applied in commercial and military aircraft.
Consortium Experience TODAY		**Medium**		Theoretical models and lab tests (technology projects).
Maturity for circular economy / Life Cycle @ EIS				Unknown.
Potential for diminishing emissions	**Low/Indirect**	Direct	High	Indirect emissions.
Operations impact	No change	**Medium**	Paradigm Shift	Aircraft ground support equipment (GSE) and maintenance tasks are already known (A320 manuals).
Complexity	**Low**			
Price Point				Unknown.

2.4.7 Absorption refrigerator

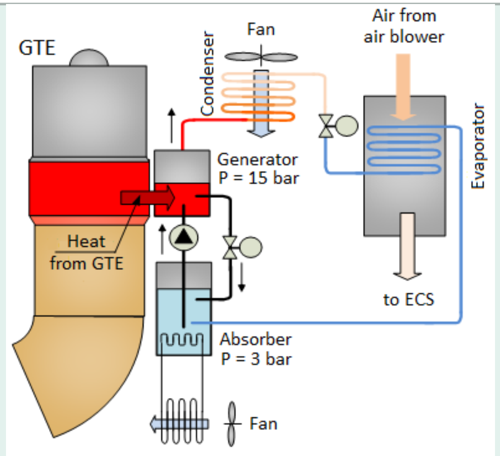
Brief Description

Absorption refrigerator is evaporation-absorption-regeneration system that uses a heat source to provide the energy needed to drive the cooling process. The refrigerant is cooled during its absorption by the absorbent.

In aircraft with HEP associated heat from the gas turbine engine can be used for operation. It is possible to use the absorption refrigerator as a pre-cooler in the thermal management system.

Working media of absorption system of aircraft thermal management system can be: Ammonia (NH3) + Water (H_2O), Lithium bromide (LiBr) or Lithium chloride (LiCl) salt + Water (H_2O).

Pictures



Technical Data

- The reduction or complete absence of electricity consumption
- Relatively low cooling coefficient (0,6 - 0,8) (compensated by the lack of power consumption)
- Working media: Ammonia (NH3) + Water (H_2O) Lithium bromide (LiBr) or Lithium chloride (LiCl) salt + Water (H_2O)

Benefits/Synergies

- Utilization of waste heat of the gas turbine
- No ozone-depleting components
- The absence of massive moving parts and vibration
- Low cost of maintenance

Drawbacks

- Low thermal dynamic
- Nature unfriendly
- Low energy efficiency

References

- Bhatia A. Overview of vapor absorption cooling systems. Stony Point: Continuing Education and Development; 2011.

2.4.7 Absorption refrigerator

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] V	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65% V	> 65%	Why?
Design tools Maturity TODAY	In house academy	General Available V	Commercial	
A/C level impact : integration synergy potential		V		GTE
Regulatory Status Readiness / Maturity TODAY	No or just working groups V	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Which emissions?
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase V	High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase V	High Increase	Why? What material needed? Etc.

2.4.8 Joule-Thomson effect

Brief Description

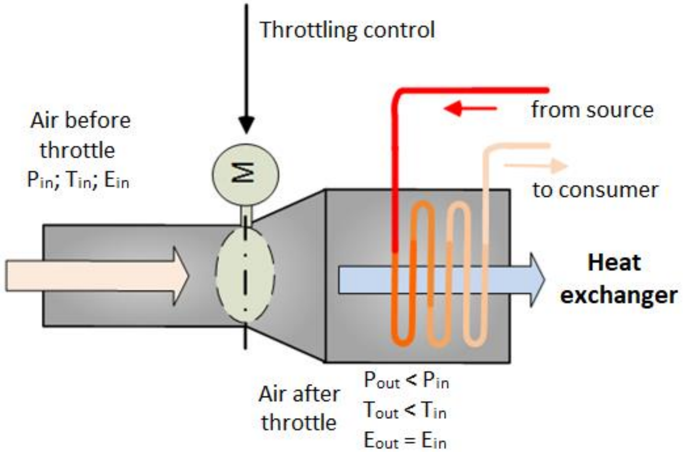
The gas-cooling throttling process is commonly exploited in refrigeration processes such as air conditioners, heat pumps, and liquefiers. The air changes its temperature when it is forced through the valve while keeping it insulated so that no heat is exchanges with the environment. No external work is extracted from the air during the expansion. Free throttling of air leads to decrease of its pressure and temperature with constant enthalpy.

Air throttling supplied to the heat exchangers of the ECS system to a pressure value close to overboard pressure will increase the efficiency of heat removal in the heat exchanger and raise the energy efficiency of the ECS.

This effect is largely achieved at cruising altitude.

The throttling due to the flow resistance in supply lines and heat exchangers is a source of losses that limits the performance.

Pictures



Technical Data

- Free throttling of air leads to decrease of its pressure (P) and temperature (T) with constant enthalpy (E)
- Throttling the air supplied to the heat exchangers (HEs) of the ECS purge system to a pressure value close to overboard pressure will increase the efficiency of heat removal in the HE and raise the energy efficiency of the ECS
- This effect is largely achieved at cruising altitude

Benefits/Synergies

- Simplicity
- Synergy

Drawbacks

- The throttling due to the flow resistance in supply lines and HEs is a source of losses that limits the performance
- Needed low ambient pressure

- References

- U.S. Patent. 4,621,279; Maier, et al.; Nov. 4, 1986; “Non-evacuated, rapidly coolable housing for an opto-electronic semiconductor component”; Telefunken Electronic GmbH, Heilbroom.
- Book: Basic Refrigeration and Air Conditioning by P. N. Ananthanarayanan, Second Edition, Tata Mc-Graw-Hill Publishing Company Limited

2.4.8 Joule-Thomson effect

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] V	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% V	Why?
Design tools Maturity TODAY	In house academy	General Available V	Commercial	
A/C level impact : integration synergy potential		V		(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups V	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Which emissions?
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase V	High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase V	High Increase	Why? What material needed? Etc.

2.4.9 Vortex tube effect

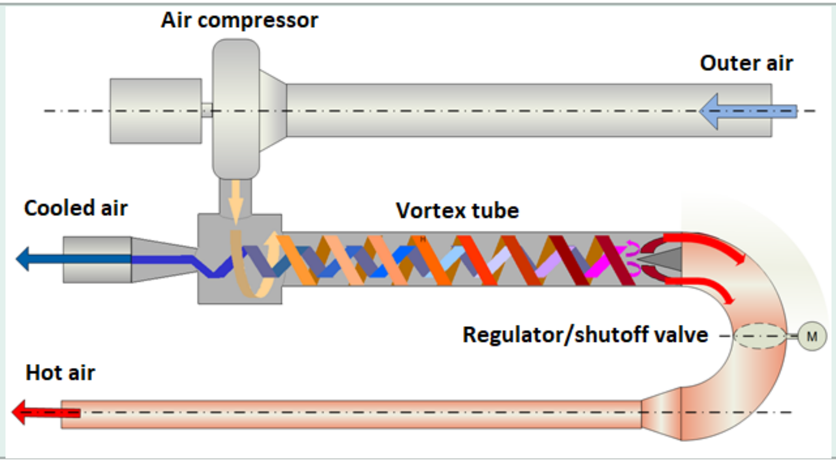
Brief Description

The vortex tube, also known as the Ranque-Hilsch vortex tube, is a mechanical device that separates a compressed gas into hot and cold streams. The vortex tube has no moving parts.

In aircraft thermal management the movement of air from the air blower will allow to get the output airflows of pre-cooled and heated air for the air-cooling preparation system.

The benefits of vortex tube are: absence of refrigerants, simple construction, no moving parts and thus high reliability, high thermal dynamic, the use of the tube can reduce the power consumption of the cooling system in the ECS air preparation system, flexible regulation is possible to optimize the parameters of the cooling-heating system overall. The drawbacks are: need to use high compressed gas to obtain low temperatures, relative low energy efficiency. However isentropic energy conversion efficiency that is now about 50% can be potentially shifted to 80%.

Pictures



Technical Data

- The hot gas temperature can reach **200 °C**, and the cold gas temperature can reach **minus 50 °C**
- Isentropic energy conversion efficiency **η ≈ 50%** but it is potentially possible to create VT with **η ≈ 80%** [3]

Benefits/Synergies

- Absence of refrigerants
- Simple construction
- No moving parts and thus high reliability
- High thermal dynamic
- The use of VT can reduce the power consumption of the cooling system in the ECS air preparation system
- Flexible regulation is possible to optimize the parameters of the cooling-heating system overall

Drawbacks

- Relative low energy efficiency
- Need to use a powerful compressor to obtain low temperatures

- References
- A. Noskov et al. Energy efficiency and economic feasibility of using artificial climate systems based on a vortex tube // Engineering and construction magazine. 2011. No. 1(19). P. 17-2. (in Russian) DOI: 10.18720/MCE.19.8.
- Azarov A. Vortex tubes of a new generation // Constructor. Mechanician. 2007. no. 3. P. 18-24. (in Russian)
- Yunpeng Xue The working principle of a Ranque-Hilsch Vortex Tube. School of Mechanical Engineering The University of Adelaide south Australia 5005 Australia, 2012.

2.4.9 Vortex tube effect

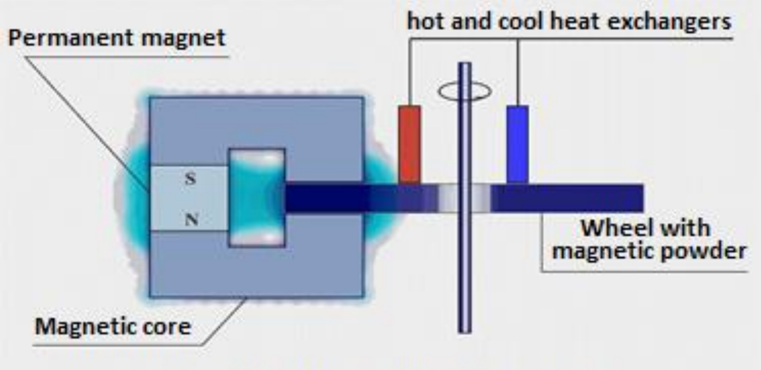
Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3] V	[4-6]	>7	
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65% V	> 65%	
Design tools Maturity TODAY	In house academy V	General Available	Commercial	
A/C level impact : integration synergy potential		V		GTE, ECS
Regulatory Status Readiness / Maturity TODAY	No or just working groups V	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Which emissions?
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase V	Medium Increase	High Increase	Why? What parts?
Price Point	No change / Minor Increase V	Medium Increase	High Increase	Why? What material needed? Etc.

2.4.10 Magnetocaloric effect

Brief Description

Magnetocaloric effect – the ability of a magnetic material (e.g., gadolinium) to change its temperature and entropy under the influence of a magnetic field. This effect can be used to build a magnetic refrigeration system in the aircraft TMS with HEP. That type of aircraft will probably generate a high magnetic field. A magnetic refrigeration system uses commonly a rotating wheel structure that consists of a wheel containing segments with gadolinium powder. The wheel heats up when it crosses the magnetic field. This heat must be withdrawn. When gadolinium exits the magnetic field, the material is further cooled and thus cool the blower air directly or using a secondary coolant system.

Pictures



Magnetic refrigeration system scheme

© AMT&C

Technical Data

Magnetic refrigeration has high thermodynamic efficiency and it is 20-30% more efficient than vapor-compression refrigeration system.

Wide operation temperature range provides wide utilization.

Relatively high output power in superconducting magnets system provides high efficiency when this technology is used with superconductivity.

Benefits/Synergies

- Low environmental hazard
- Long life cycle
- Silent
- Vibration free design
- Flexibility of technology

Drawbacks

- Immature techs for aviation
- Low efficiency
- Moving parts

- References
- Karl Gschneidner, Jr. & Kerry Gibson (December 7, 2001). "Magnetic Refrigerator Successfully Tested". Ames Laboratory News Release.
- N A Mezaal et al. “Review of magnetic refrigeration system as alternative to conventional refrigeration system.” IOP Conf. Ser.: Environ. Sci. 87 (2017) 032024.

2.4.10 Magnetocaloric effect

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3] V	[4-6]	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65% V	> 65%	Why?
Design tools Maturity TODAY	In house academy V	General Available	Commercial	
A/C level impact : integration synergy potential		V		(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups V	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Which emissions?
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase	High Increase V	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase	High Increase V	Gagolinium

2.4.11 Thermionic energy converter

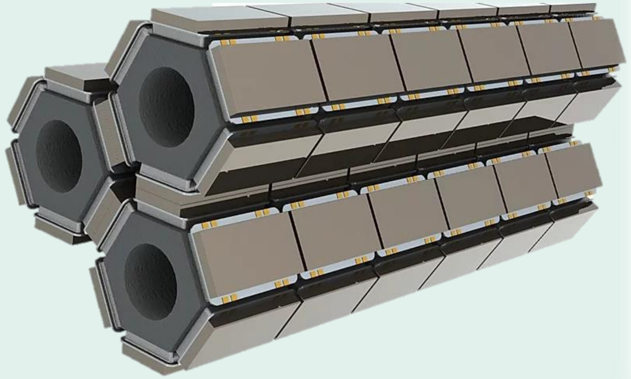
Brief Description

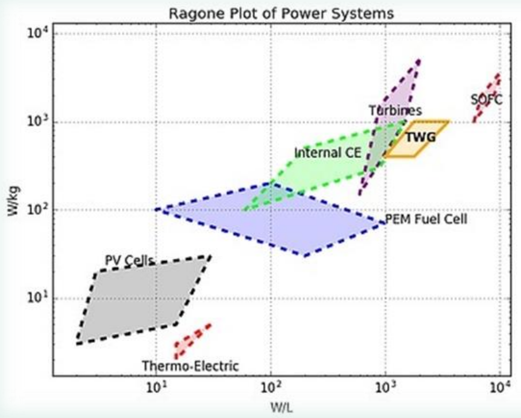
Thermionic energy converter is a heat engine that generates electricity directly using heat as its source of energy and electron as its working fluid. Despite having a huge potential as an efficient direct energy conversion device, the progress in vacuum-based thermionic energy converter development has always been hindered by the space charge problem and the unavailability of materials with low work function. [2.26]

A thermionic wave generator produces electrical power directly from heat, which drives a thermionic emission process (Edison emissions) using no moving parts or working fluid, which minimizes entropy generation in the system.

As a stand-alone system it can replace internal combustion engines (ICEs) across a range of applications, from household power through transportation. Integrated into combined heat and power (CHP) systems it can transform power generation at a range of scales (e.g., from kW–MW). The thermionic wave generator enhanced efficiency over prior thermionic systems derives from Space Charge's work to-date on addressing thermal and electromagnetic loss mechanisms.

Pictures





Technical Data

Projections from mini-prototype data & engineered models indicate:

- 65% overall conversion efficiency
- > 2x times improvement in realized prior art
- Theoretically up to 90% with an optimized system
- Operational temperature ~ 800 ℃.

Benefits/Synergies

- Low cost via wafer-fabrication and advanced material technologies.
- Energy and power densities similar to gas turbines, without working fluid, moving parts or maintenance requirements.

- References
- K. A. Abdul Khalid, T. J. Leong and K. Mohamed, "Review on Thermionic Energy Converters," in IEEE Transactions on Electron Devices, vol. 63, no. 6, pp. 2231-2241, June 2016, doi: 10.1109/TED.2016.2556751.
- S.P. Beeby, ... A. Almussallam, in Multidisciplinary Know-How for Smart-Textiles Developers, 2013.

2.4.11 Thermionic energy converter

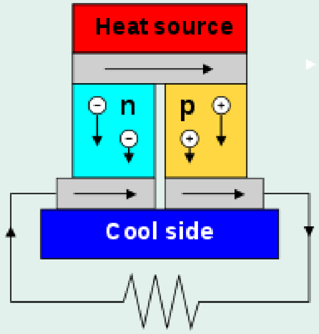
Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] V	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65% V	> 65%	Why?
Design tools Maturity TODAY	In house academy	General Available V	Commercial	
A/C level impact : integration synergy potential			V	GTE
Regulatory Status Readiness / Maturity TODAY	No or just working groups V	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Which emissions?
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase	High Increase V	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase	High Increase V	Why? What material needed? Etc.

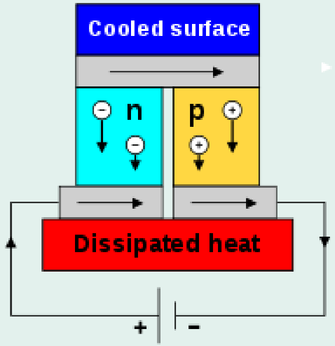
2.4.12 The thermoelectric effects: Seebeck effect and Peltier effect

Brief Description

The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice versa via a thermocouple. Seebeck effect is the buildup of an electric potential across a temperature gradient. The potential difference across the ends for two dissimilar series-connected conductors is proportional to the temperature difference between hot and cool contacts. Peltier effect is an energy transfer when an electric current pass through the junction of two dissimilar conductors, from one conductor to another. Peltier effect can be considered as the back-action counterpart to the Seebeck effect. The efficiency of the device that generates heat as a by-product can be increased by recovering the energy lost as heat. The lesser the temperature of the hot side, the greater the amount of power will be produced

Pictures





Technical Data

The value of the resulting thermo-EMF in a small temperature range depends only on the material of the conductors and the temperatures of the hot and cool contacts.

Value of thermo-EMF:

- copper-constantan: ε ≈ 4,28 mV / 100 °C

- chromel-alumel: ε ≈ 4,10 mV / 100 °C

Thermo-EMF of “classic” metals is very small (on the order of several mV/K), but for semiconductors it can exceed 1000 mV/K.

Benefits/Synergies

- Thermoelectric generators using liquid on the cold side perform better than any other cooling method and produce significantly more net additional power. However, bismuth telluride is the standard semiconductor material that can improve the efficiency of thermoelectric generators at low temperatures.

- References

- Kuhling H. Handbook of physics. - M.: Mir. - 1982. - P. 374-375. (in Russian)
- Walker, Kris. "How Can Thermo Electrical Generators Help the Environment?". AZoCleantech. https://www.azocleantech.com/article.aspx?ArticleID=361.

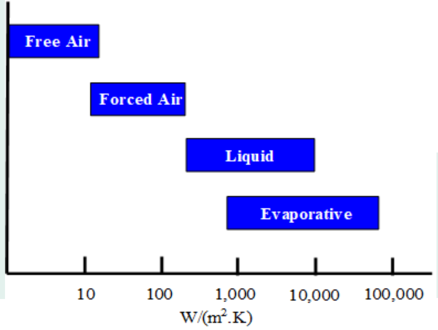
2.4.12 The thermoelectric effects: Seebeck effect and Peltier effect

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] V	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65% V	> 65%	Why?
Design tools Maturity TODAY	In house academy	General Available V	Commercial	
A/C level impact : integration synergy potential			V	GTE, ECS
Regulatory Status Readiness / Maturity TODAY	No or just working groups V	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	Which emissions?
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase V	High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase V	High Increase	Why? What material needed? Etc.

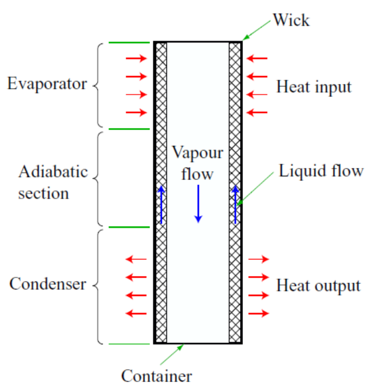
2.4.13 Passive Systems (e.g. heat pipes, thermosyphons, vapor chambers)

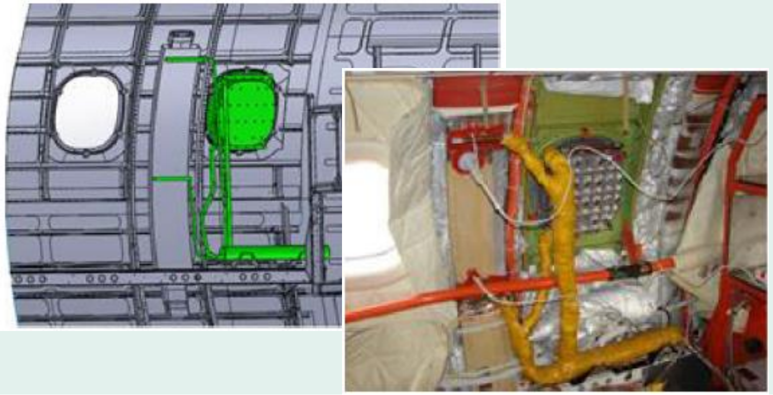
Heat pipes, defined as devices that transfer heat by a process of evaporation and condensation of a fluid circulating within a sealed cavity, exist in a variety of sizes and configurations. They all have a region where the working fluid is evaporated (evaporator) and a region where it is condensed (condenser). The fluid circulation can be driven in a number of ways, most commonly by capillary forces in a porous wick (heat pipes), but also by gravitational forces (thermosyphon). Therefore, the heat transfer is performed by the evaporation and condensation of the working fluid.

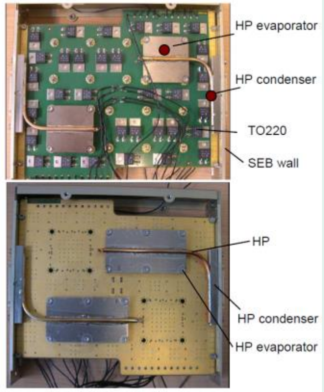
Size and weight reductions are crucial requirements for aeronautical devices, leading to high power dissipation rates per area. Heat pipes/thermosyphons/vapor chambers are devices adequate for high transfer rates (100 to 1000 more than convective air) on small surfaces, therefore, adequate for large power density equipment. Also, require low maintenance and no power consumption since are passive devices.



Heat transfer coefficients for various cooling methods.







Heat pipes can be integrated to other cooling systems such as liquid cooling loops, VCS evaporators, etc.. Also, at flight the fuselage is submitted to low temperatures and high convective heat transfer coefficients, which make perfect conditions for transferring the heat of the heat pipes condensers.

- SAE AIR1811 - Liquid Cooling Systems
- ESDU 80013 - Heat Pipes, General Information on theis Use, Operation and Design
- J.L.G. Oliveira, et al., "In-flight testing of loop thermosyphons for aircraft cooling", Applied Thermal Engineering 98 (2016) 144–156
- C. Sarno, et al., "Loop Thermosyphon For The Thermal Management Of An Aircraft Electronic Box", 16th International Heat Pipe Conference (16th IHPC), 2012

2.4.13 Passive Systems (e.g. heat pipes, thermosyphons, vapor chambers)

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TRL) TODAY	[1 – 3]	[4 – 6]	**>7**	Equipment cooling (e.g. actuators of the A350 and mainly military applications).
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%**	The technology is applied in commercial (e.g. A350) and military aircraft.
Design tools Maturity	In house academy	General Available	**Commercial**	The technology is applied in commercial (e.g. A350) and military aircraft.
A/C level impact : integration synergy potential		**Medium**		Understanding of the aircraft mission requirements, operations, etc., are essential to select heat sinks and design passive systems.
Regulatory Status Readiness / Maturity (TODAY)			**FAA Part 25, EASA CS-25, military.**	The technology is applied in commercial (e.g. A350) and military aircraft.
Consortium Experience TODAY			**High**	Theoretical models, lab tests, integration on aircraft prototypes and flight tests.
Maturity for circular economy / Life Cycle @ EIS				Unknown.
Potential for diminishing emissions	**Low/Indirect**	Direct	High	Indirect emissions.
Operations impact	No change	**Medium**	Paradigm Shift	Aircraft ground support equipment (GSE) and maintenance tasks shall be defined.
Complexity			**High**	Passive systems require several controlled fabrication processes.
Price Point				Unknown.

Appendix A3: Aircraft Designs Specs

3.1 Boundary Layer Ingestion

Brief Description

Boundary Layer Ingestion describes motors that are placed into the boundary layer of the airplane. It can be divided into asymmetric BLI and symmetric BLI.

The mechanism behind it can be split into two parts: “The first effect comes from the elimination of the wake defect itself through ingestion, while the second effect comes from the reduction of jet kinetic energy required associated with the first effect.” [1]

The symmetric version is placed at the rear of the fuselage and increases its length.

Picture

Technical Data

Less energy needed for equal thrust by lower v_{in} [2]:

- $T = \dot{m} \cdot (v_{out} - v_{in})$
- $P = 1/2 \cdot \dot{m} \cdot (v_{out}^2 - v_{in}^2)$

Gray et. al. estimate ca. 1 %...5 % power savings depending on hybridization level and power transmission efficiency [3]

Greitzer et. al. estimate 2.6 % fuel consumption reduction by BLI for the D8.5 config and 9.5 % in case of the H3.2 config [4]

Benefits/Synergies

- Increased propulsion efficiency by ingesting the low velocity boundary layer
- Wake filling reduces drag of the airplane
- Duct increases static thrust and lowers noise emissions

Drawbacks

- Distortion tolerant fan required [1]
- Maintenance
- Increased fuselage length

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.1 Boundary Layer Ingestion

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	3			According to [1] probability: 90% TRL 4 in 2025 D8.5; 80% TRL 4 in 2025 H3.2
Probability of Technology Readiness Level 6/7 in 2030		35% < P < 65%		
Design tools Maturity TODAY	In house academy			But for detailed design: CFD, FEM etc.
A/C level impact : integration synergy potential			X	Drag reduction; reduced fuel burn
Regulatory Status Readiness / Maturity TODAY		SC-E19		Proposal for Electric / Hybrid Propulsion System (excl. CS25)
Consortium Experience TODAY		X		
Maturity for circular economy / Life Cycle @ EIS			X	If CFRP used, might not be true
Potential for diminishing emissions	Indirect, in case of aerodynamic benefits	Direct, in case of higher propulsive efficiency		All combustion related by reduced fuel consumption
Operations impact		Medium		Inspection; Maintenance
Complexity			X	Distortion tolerant fan
Price Point			X	Fan is under higher stress, increased replacement rate

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.1 Boundary Layer Ingestion

References

[1] Greitzer, E.M., et al. N+3 Aircraft Concept Designs and Trade Studies. Final Report, 31 Mar 2010.

[2] Budziszewski, Nils; Friedrichs, Jens (2018): Modelling of A Boundary Layer Ingesting Propulsor. In: MDPI energies. Available from https://www.mdpi.com/1996-1073/11/4/708/pdf, last viewed 2020-04-01.

[3] Gray, Justin S.; Martins, Joaquim R. R. A. (2019): Coupled aeropropulsive design optimisation of a boundary-layer ingestion propulsor. In: Aeronaut. j. 123 (1259), p. 121–137. DOI: 10.1017/aer.2018.120.

[4] Greitzer, E. M.; Slater, H. N.; Aurora Flight Sciences; Pratt & Whitney (2010): N+3 Aircraft Concept Designs and Trade Studies. Final Report. Massachusetts Institute of Technology. Available from http://web.mit.edu/drela/Public/N+3/Final_Report.pdf, last viewed 2020-04-25.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.2 Wing Tip Propulsion

Brief Description

Wing Tip Propellers (WTP) are propellers mounted on the wingtip. The airflow in the vicinity of the wingtips results in beneficial effects in drag and/or propulsive efficiency.

Both Tractor and Pusher configurations are possible. The former is reducing drag and increases maximum lift as well as effective aspect ratio. The latter has a reduced required shaft power due to the pre-swirled inflow. Drag may also be decreased by the change in the downstream vortex field. [1]

The technology can be extended over the whole wing (distributed propulsion) and boundary layer ingestion can be added as in the case of the Eviation Alice.

Picture

Technical Data

Drastic reduction in drag possible, depending on thrust coefficient [1]

Increase in wing lift is slightly smaller due to slipstream compared to a conventional configuration [1], but covered wing span is half of the conventional.

Rotational direction of propeller has to be against wing tip vortex [2], by that the trailing vortex is moved outward [3], which reduces induced drag.

Drag reduction directly proportional to wing lift; higher aspect ratio reduces benefit [2]

Possibly a high wing configuration is suited best to allow for ground clearance and with that also the T-Tail. Otherwise the landing gear is higher.

Benefits/Synergies

- Tailoring lift distribution
- Improved Flutter and aeroelasticity characteristics

Drawbacks

- Asymmetric thrust requires a big vertical tail or additional propulsion, that is capable of providing enough thrust fur OEI condition
- Manoeuvring capabilities of WTPs, lower than compared to DEP

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.2 Wing Tip Propulsion

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY		4-5		Icaré WTP
Probability of Technology Readiness Level 6/7 in 2030			> 65%	Eviation Alice was already in ground testing before fire damage
Design tools Maturity TODAY	In house academy			But for detailed design: CFD, FEM etc.
A/C level impact : integration synergy potential			X	Tip vortex
Regulatory Status Readiness / Maturity TODAY		SC-E19		Proposal for Electric / Hybrid Propulsion System (excl. CS25)
Consortium Experience TODAY		X		TU Delft, USTUTT
Maturity for circular economy / Life Cycle @ EIS			X	If CFRP used, might not be true
Potential for diminishing emissions	Indirect, in case of aerodynamic benefits	Direct, in case of reduced shaft power		All combustion related by reduced fuel consumption
Operations impact	No change			
Complexity		X		New systems, longer cables
Price Point	X			Propellers and electric motors are “known” technology

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.2 Wing Tip Propulsion

References

[1] Hepperle, M. Aspects of Distributed Payload. A View on Regional Aircraft. Stuttgart, 19 Feb 2016. E2Flight Conference.

[2] Borer, N.K., et al. Comparison of Aero-Propulsive Performance Predictions for Distributed Propulsion Configurations. In: AIAA SciTech Forum. 55th AIAA Aerospace Sciences Meeting. 2017, p. 246. ISBN 978-1-62410-447-3

[3] Miranda, L. and Brennan, J.. Aerodynamic effects of wingtip-mounted propellers and turbines. In: 4th Applied Aerodynamics Conference. Reston, Virginia: American Institute of Aeronautics and Astronautics, 1986-09-06

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.3.1 Distributed Propulsion – Cruise Configuration

Brief Description

By distributed propulsion (DP) the main propulsors are separated into multiple motors that are distributed over the wing. Pusher as well as tractor configurations are thinkable.

In most drafts, DP is used over the whole wing, so at the tips there are Wing Tip Propellers. The diameter of the blades can differ between inside and at the tip (compare X-57).

Two configurations are possible: By a cruise configuration the bypass-ratio is increased. In both cases the wing area can be reduced and the wing loading increased.

Can also be combined with Boundary Layer Ingestion as it is the case of the lilium jet.

Picture

Technical Data

Increased propeller area which increases bypass ratio [1]

This results in increased efficiency (smaller Δv for same thrust) and reduced noise [1]

Rudder and vertical tail size can be reduced by linear thrust variation over the wing [3]

Benefits/Synergies

- Increased efficiency and reduced noise by a reduction in propeller loading
- DEP yaw capabilities which allow reduced Vertical Tailplane Size
- Tailoring lift distribution
- Redundancy/Safety improvement
- Improved flutter and aeroelasticity characteristics

Drawbacks

- Large amount of components
- Complex architecture
- Propeller at wing tip might influence operations

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.3.1 Distributed Propulsion – Cruise Configuration

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	4			
Probability of Technology Readiness Level 6/7 in 2030		35% < P < 65%		Certification issues
Design tools Maturity TODAY	In house academy			But for detailed design: CFD, FEM etc.
A/C level impact : integration synergy potential			X	tip vortex; differential thrust
Regulatory Status Readiness / Maturity TODAY		SC-E19		Proposal for Electric / Hybrid Propulsion System (excl. CS25)
Consortium Experience TODAY		X		TUDelft
Maturity for circular economy / Life Cycle @ EIS			X	If CFRP used, might not be true
Potential for diminishing emissions	Indirect			All combustion related by reduced fuel consumption
Operations impact	No change			Lower failure probability
Complexity			X	More motors, more systems, more cables
Price Point		X		Number of motors, systems, cables and maybe dissimilar approach

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.3.1 Distributed Propulsion – Cruise Configuration

References

[1] Hepperle, M. Aspects of Distributed Payload. A View on Regional Aircraft. Stuttgart, 19 Feb 2016. E2Flight Conference.

[2] Kim, H.D., A.T. Perry und P.J. Ansell. A Review of Distributed Electric Propulsion Concepts for Air Vehicle Technology, 2018

[3] Miranda, L. and Brennan, J.. Aerodynamic effects of wingtip-mounted propellers and turbines. In: 4th Applied Aerodynamics Conference. Reston, Virginia: American Institute of Aeronautics and Astronautics, 1986-09-06

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.3.2 Distributed Propulsion – High-Lift Configuration

Brief Description

DP as high lift system where the whole system is only operated in the start and landing phase at low velocities. It consists of main propellers and smaller propellers (high-lift) which can be retracted in flight.

Picture

Technical Data

Flaps and slats can be replaced

Allows reduced wing area and wing optimization for cruise [2]

Inner propellers of X-57 Maxwell only active for start/landing but requires special propellers with near uniform axial velocity profile [2]

Benefits/Synergies

- Distributed High-Lift Propellers replace complex flaps and slats
- Reduced Vertical Tailplane Size
    - WTP/(DEP) yaw capabilities
- Tailoring lift distribution
- Improved flutter and aeroelasticity characteristics
- Drag reduction by smaller wing [2]

Drawbacks

- Challenging Certification:
    - Asymmetric thrust requires a big vertical tail or additional propulsion to both WTPs, that is capable of providing enough thrust fur OEI condition
- Large amount of components
- Complex architecture
- Propeller at wing tip might influence operations

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.3.2 Distributed Propulsion – High-Lift Configuration

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	3			X-57 Truck Testbed
Probability of Technology Readiness Level 6/7 in 2030		35% < P < 65%		X-57 Phase 2 this year; Phase 4 required for TRL5; EcoPulsePM Maiden flight 2022
Design tools Maturity TODAY	In house academy			But for detailed design: CFD, FEM etc.
A/C level impact : integration synergy potential			X	High lift system; tip vortex; differential thrust
Regulatory Status Readiness / Maturity TODAY		SC-E19		Proposal for Electric / Hybrid Propulsion System (excl. CS25)
Consortium Experience TODAY		X		TU Delft
Maturity for circular economy / Life Cycle @ EIS			X	If CFRP used, might not be true
Potential for diminishing emissions	Indirect			All combustion related by reduced fuel consumption
Operations impact	No change			Lower failure probability
Complexity			X	More motors, more systems, more cables
Price Point		X		Number of motors, systems, cables and maybe dissimilar approach

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.3.2 Distributed Propulsion – High-Lift Configuration

References

[1] Hepperle, M. Aspects of Distributed Payload. A View on Regional Aircraft. Stuttgart, 19 Feb 2016. E2Flight Conference.

[2] Borer, N.K., et al. Comparison of Aero-Propulsive Performance Predictions for Distributed Propulsion Configurations. In: AIAA SciTech Forum. 55th AIAA Aerospace Sciences Meeting. 2017, p. 246. ISBN 978-1-62410-447-3

[3] Miranda, L. and Brennan, J.. Aerodynamic effects of wingtip-mounted propellers and turbines. In: 4th Applied Aerodynamics Conference. Reston, Virginia: American Institute of Aeronautics and Astronautics, 1986-09-06

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.4 Hydrogen Aircraft

Brief Description

Hydrogen offers 3 times the specific energy of conventional jet fuel (142 MJ/kg, 46 MJ/kg), but has in liquid form (boiling point 20K) a more than 10 times lower density than jet fuel at 1 bar (0.071 kg/m³, 0.78 kg/m³). This results in a 3 to 4 times lower energy density.

All in all hydrogen requires cooling, insulation and bigger (pressurized) cylindrical tanks.

Hydrogen can be either burnt within a conventional gas turbine or used by fuel cells to directly convert the fuel into electric energy. The reaction product is water vapor and in case of the gas turbine with ambient air also small amounts of nitrogen oxides (comp. [2]).

Infrastructure for refueling and production is limited for now.

TU-155 was flown about 100 times with LH2 and LNG – maiden flight 1988.

Picture

Technical Data

MTOM Long Range AC ca. 15 % smaller than for kerosene; OME ca. 20-25 % increased; Specific energy consumption increased by 8-15 % (wetted area; higher mean flight mass) [1]

Safety: primarily psychological problem, no detonation in free atmosphere; no fire carpet; fast burning, low heat radiation; non toxic [1]. Hydrogen burn radius is smaller than of kerosene [1,2]

Hydrogen aircraft might be safer, a fire lasts only a short time, therefore the fuselage is kept intact [2]

Oxyhydrogen “Knallgas” requires a mixture of hydrogen and oxygen between 18 % and 76 % hydrogen; between 4 % and 18 % hydrogen is burning without explosion

“Hydrogen-based engines run cooler than those using kerosene and this fact translates into a significantly longer engine life.” [5]

Benefits/Synergies

- Cooler engine temperature -> longer life
- Reduced fuel mass
- Reduced greenhouse gases
- Fast burning, no fire carpet, low heat radiation
- Synergy with thermal system
- Synergy with electrical system/wiring: superconductivity

Drawbacks

- Requires cooling; boil-off losses
- Insulation of tank and pipes
- Tank: form (cylindrical)/size/volume
- Certification
- New infrastructure required at airports
- Risk of aviation induced cloudiness (depending on altitude, maybe lower impact and duration)

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.4 Hydrogen Aircraft

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY		4 (Fuel cell) 5 (burning)		HY4 fuell cell; Boeing Fuel Cell Demonstrator; TU-155
Probability of Technology Readiness Level 6/7 in 2030		35% < P < 65% (Fuel Cell)	> 65% (Burning)	TRL already high; depending on funding
Design tools Maturity TODAY	In house academy			
A/C level impact : integration synergy potential			X	Thermal & electrical
Regulatory Status Readiness / Maturity TODAY	No or just working groups			HY4, Boeing Fuel Cell Demonstr.: permit to fly
Consortium Experience TODAY	X			
Maturity for circular economy / Life Cycle @ EIS		X		CFRP tank
Potential for diminishing emissions			High	CO2; NOx & Noise (in case of fuel cell)
Operations impact			Paradigm Shift	Infrastructure etc.
Complexity			X	Tanks under high pressure, cooling required
Price Point			X	Infrastructure cost will be priced into fuel price, for the plane itself probably only minor increase

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.4 Hydrogen Aircraft

References

[1] Faaß, R. Cryoplane. Flugzeuge mit Wasserstoffantrieb. Hamburg, Airbus, 6 Dec 2001.

[2] Maniaci, D.C. Operational Performance Prediction of a Hydrogen-Fueled Commercial Transport [online], 2006. Available from: https://web.archive.org/web/20060905121155/http://www.engr.psu.edu/symposium2006/papers/Session%203E%20-%20Energy/Maniaci.doc

[3] Corchero, G. and Montañés, J.L. . An approach to the use of hydrogen for commercial aircraft engines [online]. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2005, 219(1), p. 35-44. ISSN 0954-4100. Available from: doi:10.1243/095441005X9139

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.6 Structural Batteries

Brief Description

Structural Batteries are materials or structures able to carry load as well as storing energy to reduce system mass.

There are two possible ways to manufacture a structural battery. The first is the multifunctional structure (MFS), where thin conventional batteries are embedded in structural components. The second way is to make a multifunctional material (MFM) where every component has to fulfill multiple purposes [1]. MFS is critical for load transfer and also delamination of the battery and load bearing structure – but MFM research of application in aircraft is limited [1].

Pictures

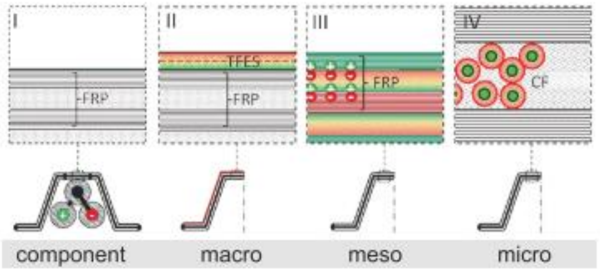


FIGURE 1. Degrees and scales of structural power components demonstrated for an omega stringer (adapted from [23, Fig. 2])

Technical Data

51.8 Wh/kg required for multifunctional material in a 2-seater all electric aircraft [2]

"There is often an inverse relationship between the mechanical and electrochemical properties of multifunctional materials […]" [1]

"In modern aircraft, the wiring often accounts for a substantial amount of weight. […] In contrast to conventional aircraft, in MFM aircraft all consumers can be connected to the battery/structure locally." [2]

"Incorporating MFM in the whole aircraft structure, including in its skin, improves the heat transfer through convection." [2]

Benefits/Synergies

Mass reduction by:

- Combination of load bearing structure with energy storage
- Less cables, consumers can be connected close to their location [2]
- Improved heat transfer [2]

Drawbacks

- Energy storage capabilities without reducing mechanical properties
- Specific energy needs improvement
- Number of charge cycles and charging time
- Replacement of malfunctioning cells and life cycle (usability as primary structure)

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.6 Structural Batteries

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	2-3			MFM / MFS
Probability of Technology Readiness Level 6/7 in 2030	< 35%			Low TRL right now, many challenges
Design tools Maturity TODAY	In house academy			
A/C level impact : integration synergy potential			X	Cable length; thermal system; Load bearing and energy storage
Regulatory Status Readiness / Maturity TODAY	No or just working groups			CS-25.1353(c) for “normal batteries”
Consortium Experience TODAY	X			
Maturity for circular economy / Life Cycle @ EIS	X			CFRP used, today no concept available
Potential for diminishing emissions			High	CO2, NOx, H2O, Noise
Operations impact		Medium (for short charging time)	High (for long charging time, especially FE)	recharging time; ground equipment: Hybrid or full-electric?
Complexity			X	Coating of single fibers etc.
Price Point			X	Coating of fibres, re-usage not possible, life-time cycle?

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

3.6 Structural Batteries

References

[1] Adam, T. et al. (2018): Multifunctional Composites for Future Energy Storage in Aerospace Structures. In: *Energies* 11 (2), p. 335. DOI: 10.3390/en11020335.

[2] Scholz, A.E.; Hermanutz, A.; Hornung, M. (2018): Feasibility Analysis and Comparative Assessment of Structural Power Technology in All-Electric Composite Aircraft.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

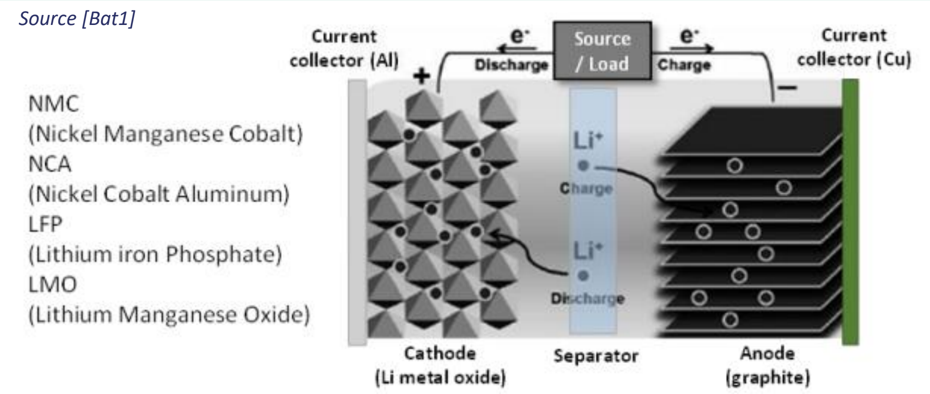
4.1 Lithium-ion battery: the cell

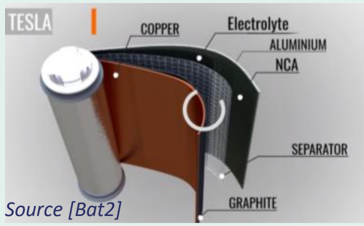
Lithium-ion batteries (also called **LiB**) are widely used in many applications today such as automotive or mobile phones.

The cell is made of a **negative** electrode (**anode**) and a **positive** electrode (**cathode**). Electrodes are connected to current **collectors** and separated with a porous **separator**, which avoids short circuit between both electrodes, soaked with **electrolyte**. Cell's components are packaged inside a rigid or a flexible **casing**.

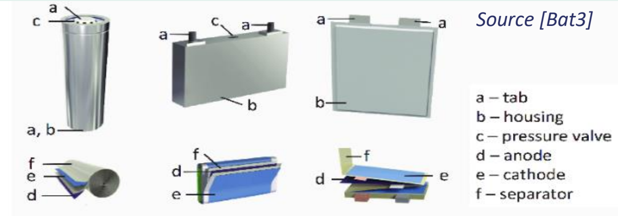
The working principle of a lithium-ion **cell** is based on the intercalation/de-intercalation of **Li^+** into the electrode materials. During the **discharge**, the Li^+ are removed from the anode. They migrate into the electrolyte and pass through the separator. Then, they insert into the cathode. At the same time, the charge transfer takes place on the electrode-electrolyte interface. The current is therefore created. During the **charge**, the displacement of Li^+ is opposite.

For **safety**, cells are designed with internal protections such as, for instance, venting. The cell's **thermal runaway**, even if the failure occurrence is very low, is difficult to prevent. Therefore, the cell must be chosen and the pack must be designed (ex: gas ejection management) to **avoid thermal runaway propagation**.


Source [Bat1]



Source [Bat2]


Source [Bat3]

Technical Data

Cell's main formats : cylindrical such as 18650 (= 18mm diameter and 65mm height), 26650, 21700, prismatic, pouch.

Cell's capacity : from a few mAh to more than 100 Ah

RTCA standard for li-ion battery in aeronautics: "**DO-311A**"

Benefits

- No emission
- Energy density (compared to other batteries)
- Efficiency

Drawbacks

- Safety to be considered during the design
- Weight (compared to fossil fuel)
- Recycling (to be improved); critical materials for some chemistries (ex cobalt)

Synergies

- Energy management
- Energy harvesting
- Thermal management
- Hybridation (with ICE, with other energy sources like fuel cells?)
- Architectures (electrics, mechanics, thermal)

4.1 Lithium-ion battery: chemistry and performance trade-off

Many **chemistries** can be used for lithium-ion batteries. The negative electrode can be made of **graphite**, of **blend Si-graphite** and sometimes of **LTO** (Lithium Titanate Oxide). The positive electrode is generally made of **NMC** (Lithium-Nickel-Manganese-Cobalt), **NCA** (Lithium-Nickel-Cobalt-Aluminium-Oxyde), **LMO** (Lithium-Manganese-Oxyde), **LCO** (Lithium-Cobalt-Oxyde), **LFP** (Lithium-Iron-Phosphate).

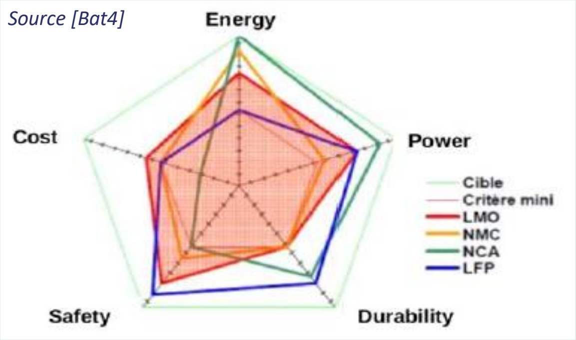
Chemistries have **different performances** in terms of **energy density, power, cyclability, safety, temperature range, environmental impact, cost**, etc. **A trade-off** is then necessary. For instance, the battery with the highest energy density will not have the highest power density and the highest safety.

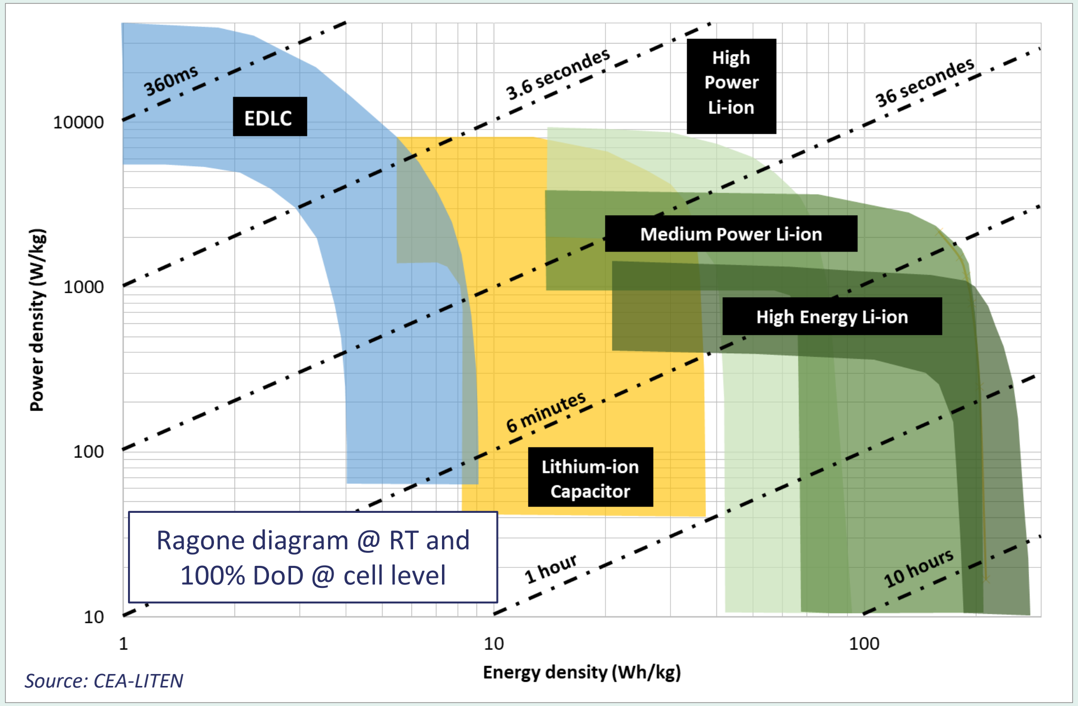
Temperature, current, state of charge, depth of discharge, influence the maximum energy, power, lifetime, and safety of the battery.

Technical Data

At cell level

	Example of a High energy cell	**Example of a High power cell**
Chemistry	NMC / Si-Graphite	LCO / hard carbon
Voltage (min / nom / max)	2,5 V / 3,6 V / 4,2 V	2,5 V / 3,6 V / 4,2 V
Energy density (gravimetric)	**~ 250 Wh/kg**	~ 90 Wh/kg
Energy density (volumetric)	~ 700 Wh/L	~ 140 Wh/L
Power density peak discharge (gravimetric)	~ 1 000 W/kg	**~ 3 000 W/kg**
Power density peak discharge (volumetric)	~ 3 000 W/L	~ 4 600 W/L
Charge rate	~ 2 C	~ 10 C
Life cycle	~ 1 000 cycles 80%DoD	~ 10 000 cycles 30%DoD
Calendar life	10 years	10 years
Temperature range	-20 °C / 60 °C discharge 0 °C / 60 °C charge	-20 °C / 60 °C discharge 0 °C / 60 °C charge
Efficiency (charge)	~ 97 %	~ 97 %


Source [Bat4]



Ragone diagram @ RT and 100% DoD @ cell level

Source: CEA-LITEN

4.1 Current lithium-ion battery

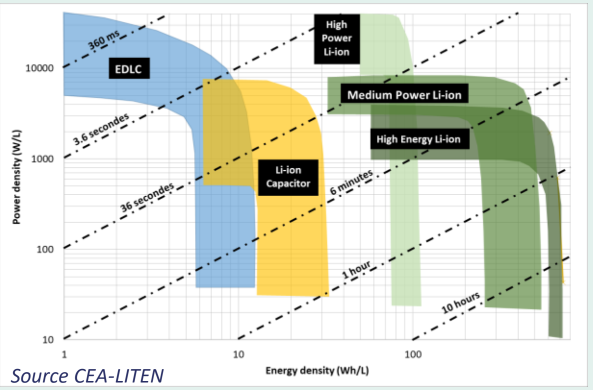
Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6]	>7 ✓	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% ✓	Why?
Design tools Maturity TODAY	In house academy	General Available ✓	Commercial	
A/C level impact : integration synergy potential	✓			(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23 ✓	Special Condition CS23 / CS 25	
Consortium Experience TODAY			✓	What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS		✓		Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High ✓	Which emissions?
Operations impact	No change	Medium ✓	Paradigm Shift	
Complexity	No change / Minor Increase ✓	Medium Increase	High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase ✓	High Increase	Why? What material needed? Etc.

4.1 Supercap - LiC

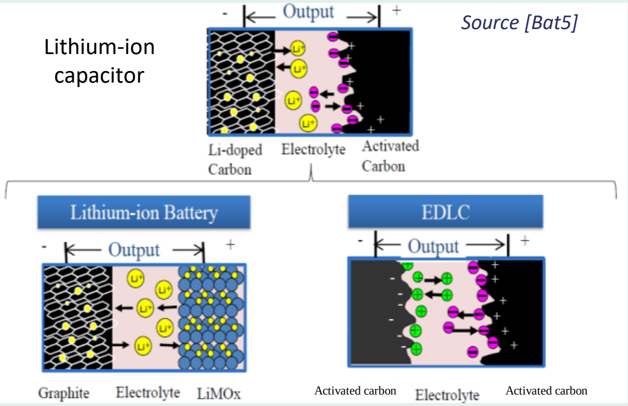
Supercaps (also called **EDLC** for ‘Electric Double Layer Capacitors’) do not involve chemical reaction. They demonstrate high power and long operating life. Both electrodes are similar. Their energy density is 10 to 100 times those of standard capacitors, but remains far lower from lithium-ion batteries.

LiC (or ‘**Li-ion Capacitors**’) are **hybrid** devices between supercap and lithium-ion batteries. They combine the intercalation mechanism of lithium batteries with the cathode of an EDLC. Their performances are therefore intermediate between batteries and supercap.

Neither supercap nor LiC can completely replace batteries for applications that require high energy. Nevertheless, they can be used additionaly to another storage source to **deliver high peak currents during a very short time**.



Source CEA-LITEN



Source [Bat5]

Technical Data

At cell level	**Supercap**	**LiC**
Energy density (gravimetric)	˜ 7 Wh/kg	˜ 20 Wh/kg
Energy density (volumetric)	˜ 10 Wh/L	˜ 15 Wh/L
Power density peak discharge (gravimetric)	˜ 15 kW/kg	˜ 6 kW/kg
Power density peak discharge (volumetric)	˜ 15 kW/L	˜ 7 kW/L
Life cycle	˜ 1 000 000 cycles 50%DOD	˜ 200 000 cycles 50%DOD
Calendar life	20 years	10 years
Temperature range	-40 °C / 65 °C	-20 °C / 60 °C

Benefits

- High cyclability
- Wide T operation range
- May improve the battery lifetime or size with hybridization (depends on the system sizing)

Drawbacks

- Not able to deliver high energy alone
- Additional component (system is more complex)

Synergies

- Energy management
- Hybridation (ex: with ICE, batteries, fuel cell …)
- Architectures (electric, mechanics, thermal)

4.1 Battery hybridization with supercap or LiC

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] ✓	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% ✓	Why?
Design tools Maturity TODAY	In house academy	General Available ✓	Commercial	
A/C level impact : integration synergy potential	✓			(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23 ✓	Special Condition CS23 / CS 25	
Consortium Experience TODAY			✓	What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS		✓		Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High ✓	Which emissions?
Operations impact	No change	Medium ✓	Paradigm Shift	
Complexity	No change / Minor Increase ✓	Medium Increase	High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase ✓	High Increase	Why? What material needed? Etc.

4.2 Solid state batteries (prospective)

Solid state batteries substitute the liquid electrolyte with a **solid polymer or a ceramic separator**. They do not use flammable liquid electrolyte and aim at providing **higher safety**.

Solid state batteries are often expected to be **combined with pure lithium negative electrode** instead of classical graphite. The lithium-metal electrode ('**lithium-metal battery**') achieves high specific energy. However, it induces safety hazards due to **dendrites** growth. The solid state battery is then perhaps a solution to unlock the safe use of metallic lithium.

Nevertheless, safety gain from solid-state batteries is **not completely proved** yet. Indeed, even without internal short-circuit, some other dangerous phenomena could occur and lead to gas generation and thermal runaway. Especially, O2 release from the cathode must be studied.

Solid state batteries still are at research phase. Studies generally focus at the solid electrolyte material, **conductivity, stability, interfaces,** and battery **processability**. Safety must also be checked.

Technical Data

Very optimistic (prospective+theoric)

Simulations:

	Current Li-ion	Optimistic Li-ion*	Optimistic Li-Sulfur*	Optimistic Li-Air*
Specific Energy Density - Wh(total)/kg (cell)	250	530	550	710
Specific Energy Density - Wh(total)/kg (system)	**150**	**290**	**300**	**280**
Energy Density - Wh(total)/liter (cell)	520	1050	620	760
Energy Density - Wh(total)/liter (system)	**230**	**375**	**260**	**240**

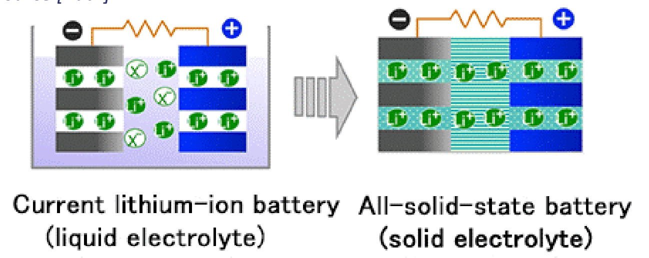
Source [Bat19]

*Assumes Li-metal negative

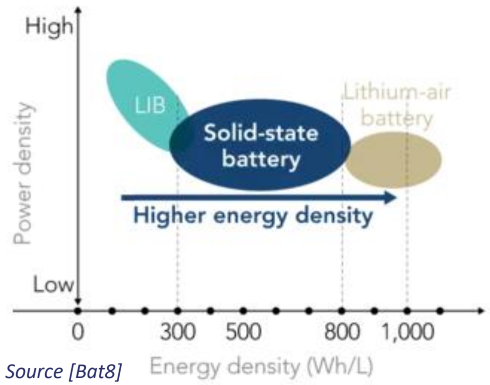
Commercial batteries:

Bolloré Blue-car uses a 'LMP' (Lithium-Metal-Polymer) battery. Nevertheless it must operate at high T (˜ 80 °C) to compensate the low conductivity. The vehicle must then be plugged for charging, and the safety margin for high T is reduced. Moreover, its energy density remains much lower (-30%) than best Li-ion battery packs of electric vehicles.

Source [Bat7]



Toyota Motor's proposed battery development roadmap



Source [Bat8]

Benefits
- Safety (but not completely proven yet)
- Can be combined with lithium negative electrode (high energy density)

Drawbacks
- Conductivity needs to be improved
- Not mature yet

Synergies
- -

4.2 Solid state battery with lithium metal anode

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3] ✓	[4-6]	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65% ✓	> 65%	Why?
Design tools Maturity TODAY	In house academy ✓	General Available	Commercial	
A/C level impact : integration synergy potential	✓			(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23 ✓	Special Condition CS23 / CS 25	
Consortium Experience TODAY		✓		What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS	✓			Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High ✓	Which emissions?
Operations impact	No change	Medium ✓	Paradigm Shift	
Complexity	No change / Minor Increase ✓	Medium Increase	High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase	High Increase	Why? What material needed? Etc.

4.2 Lithium-sulphur batteries (prospective)

Lithium-sulphur (**Li-S**) batteries are made of a lithium metal anode and a sulphur based cathode. Lithium and sulphur have a very **low weight**, thus leading to a **high specific energy density**.

The Li-S cell utilizes sulfur in place of heavy metals such as cobalt, therefore improving the **environmental** impact. Its **cost** projections are also lower than for lithium-ion batteries.

The technology is in laboratory development phase, even if a few products are already commercialized. In all cases, **energy and cycle life still need to be improved**.

Technical Data

Simulations:

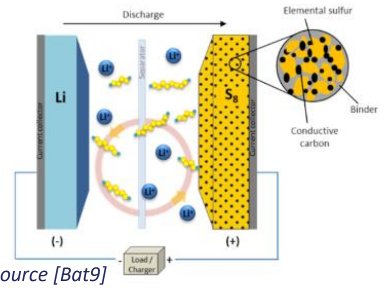
	Current Li-ion	Optimistic Li-ion*	Optimistic Li-Sulfur*	Optimistic Li-Air*
Specific Energy Density - Wh(total)/kg (cell)	250	530	550	710
Specific Energy Density - Wh(total)/kg (system)	**150**	**290**	**300**	**280**
Energy Density - Wh(total)/liter (cell)	520	1050	620	760
Energy Density - Wh(total)/liter (system)	**230**	**375**	**260**	**240**

Source [Bat19]

*Assumes Li-metal negative

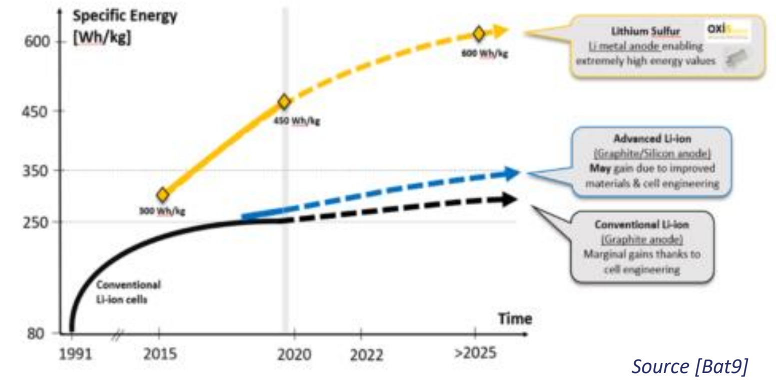
Commercial batteries:

Oxis Energy cells = 325 Wh/kg - 200 cycles or 220 Wh/kg - 1400 cycles 80%DoD



Source [Bat9]

Source [Bat9]



Source [Bat9]

Benefits

- Lightweight
- Cheap, abundant and non toxic materials

Drawbacks

- Cycle life and energy need to be improved
- Not mature yet

Synergies

- -

4.2 Lithium-sulphur battery

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	[1-3] ✓	[4-6]	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65% ✓	> 65%	Why?
Design tools Maturity TODAY	In house academy ✓	General Available	Commercial	
A/C level impact : integration synergy potential	✓			(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23 ✓	Special Condition CS23 / CS 25	
Consortium Experience TODAY		✓		What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS	✓			Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High ✓	Which emissions?
Operations impact	No change	Medium ✓	Paradigm Shift	
Complexity	No change / Minor Increase ✓	Medium Increase	High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase	High Increase	Why? What material needed? Etc.

4.2 Lithium-air (exploratory)

Lithium-air (or **lithium-oxygen Li-O_2**) batteries are often presented as an ultimate future battery for energy density.

Li-O_2 batteries typically contain a Li metal negative electrode and a positive electrode most often composed of a porous carbon material, an aqueous or nonaqueous electrolyte, and the oxygen containing gas phase.

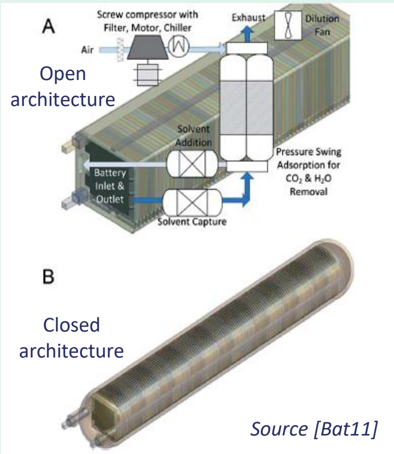
Its **theoretical specific energy is very high**. Nevertheless, for lithium-air battery operation, the system must **deliver and purify, or enclose the gaseous oxygen reactant**. The **open-architecture** requires a compressor and components for separation and solvent processes. The **close-architecture** requires a pressure vessel, which encloses pure oxygen.

When taking these extra components into account, the lithium-air battery performances, **at system level**, are projected to have **comparable cost, volume, and mass to other advanced chemistries** that are in more mature states of development and have less technical risk.

These projections need of course to be confirmed with future developments as the technology is only at **exploratory phase** for the moment.

Source [Bat10]

$$2Li(s) + O_2(g) \leftrightarrow Li_2O_2(s)$$
$$U_0 = 2.96\text{ V vs. Li}$$



Source [Bat11]

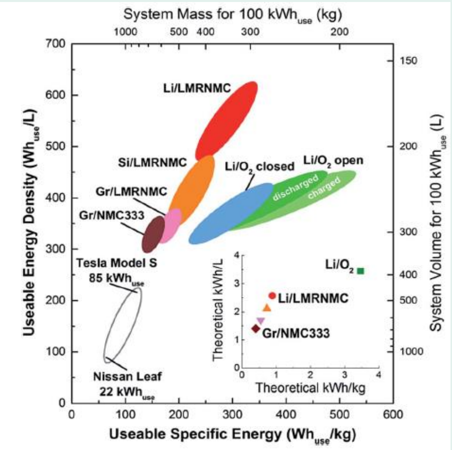


Fig. 3 Calculated systems-level energy density and specific energy fo 100 kW h of useable energy and 80 kW of net power at a nomin voltage of 360 V. (inset) Theoretical specific energy and energy densit considering both anode and cathode active materials.

Source [Bat11]

Technical Data

Theory at material level: ˜ 1 300 Wh/kg

Simulations:

	Current Li-ion	Optimistic Li-ion*	Optimistic Li-Sulfur*	Optimistic Li-Air*
Specific Energy Density - Wh(total)/kg (cell)	250	530	550	710
Specific Energy Density - Wh(total)/kg (system)	**150**	**290**	**300**	**280**
Energy Density - Wh(total)/liter (cell)	520	1050	620	760
Energy Density - Wh(total)/liter (system)	**230**	**375**	**260**	**240**

Source [Bat19]

*Assumes Li-metal negative

Benefits

- Extremely high theoretical energy density at material level

Drawbacks

- Performance drop at system level because of additional components to purify O2.
- Not mature at all.

Synergies

- -

4.2 Lithium-air battery

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	✓ [1-3]	[4-6]	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	✓ < 35%	35% < P < 65%	> 65%	Why?
Design tools Maturity TODAY	✓ In house academy	General Available	Commercial	
A/C level impact : integration synergy potential	✓			(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	✓ No or just working groups	GA or CS23	Special Condition CS23 / CS 25	
Consortium Experience TODAY	✓			What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS	✓			Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	✓ High	Which emissions?
Operations impact	No change	Medium	✓ Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase	✓ High Increase	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase	High Increase	Why? What material needed? Etc.

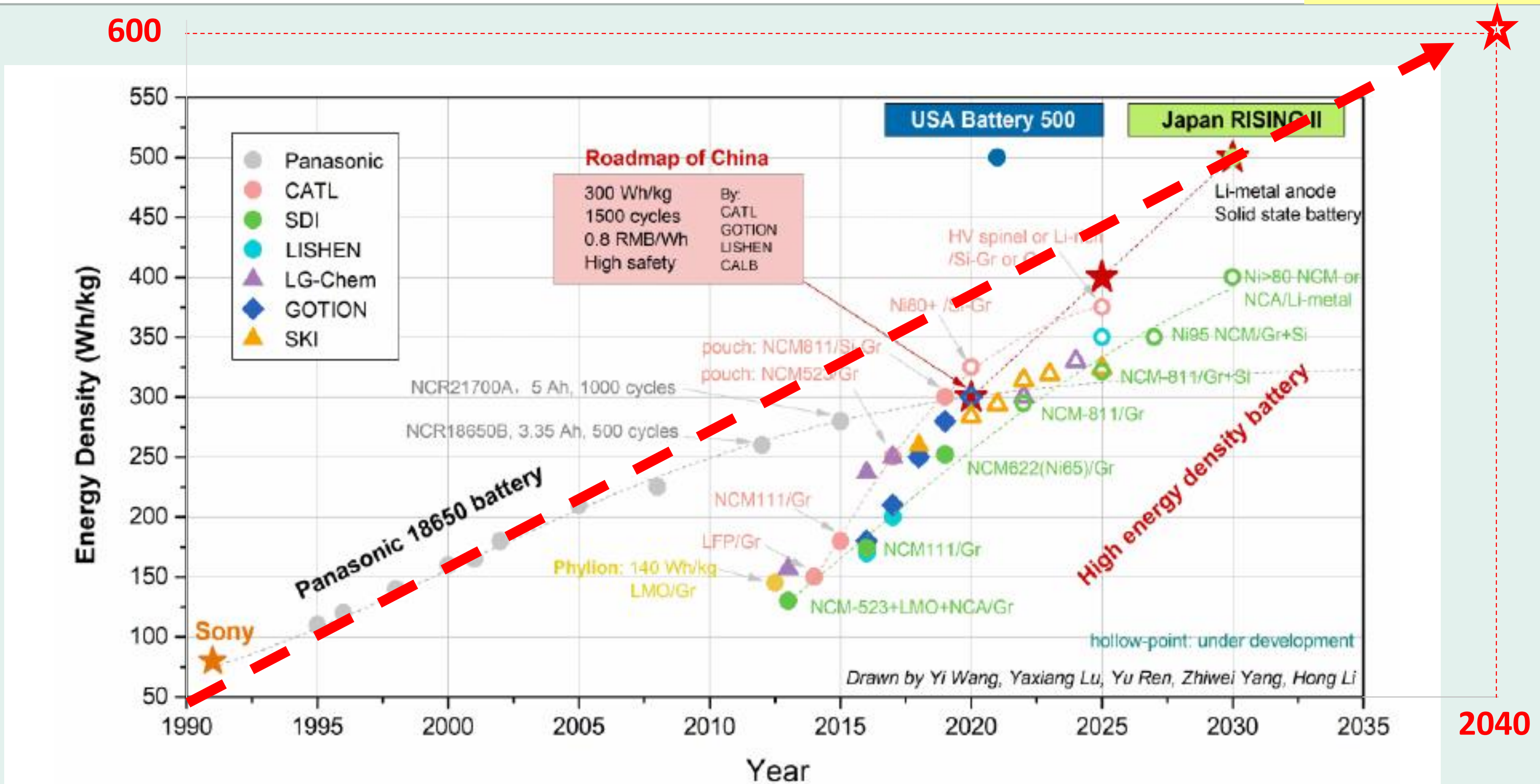
4.2 Future battery (roadmap for energy)

Many roadmaps exist.

Some are extremely different.

Here is a graph compiling
China / USA / Japan / Europ roadmaps.

Cell level:
600Wh/kg???



Source [Bat6]

4.3 Battery safety

Several accidents are well known for LIB: Galaxy S7, Boeing Dreamliner, etc. Consequences may be dramatic. **Safety** is then a major point in lithium-ion battery, which must be considered from the **very beginning of the conception** and at **every level** (cell's chemistry, cell's design and internal protection, BMS protections, pack protections, battery architecture, etc).

The cell's **thermal runaway** is one of the main issue. It appears when the internal energy from the exothermic reactions passes over the energy that can be dissipated. The origin can come from different causes, some of them being very difficult to anticipate (such as an internal short-circuit initiated from dendrites growth). The result is an increase of the cell's temperature and a series of reactions with a non-return point.

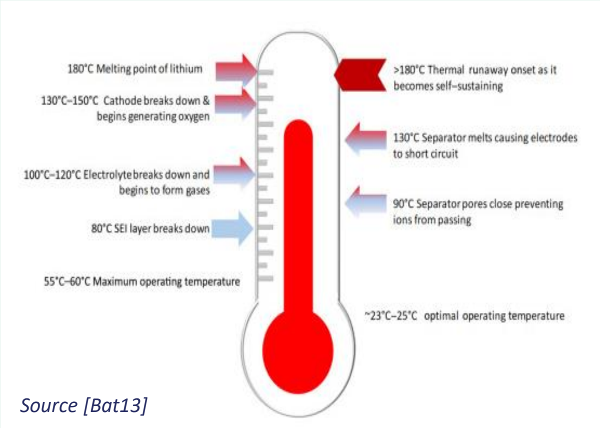
If a thermal runaway appears on a cell, the goal is then that it degases without exploding and that it **does not propagate to the other cells** and to the entire pack with fire. **The gas ejection** in such case must then be managed.

Typical **safety tests** for battery:

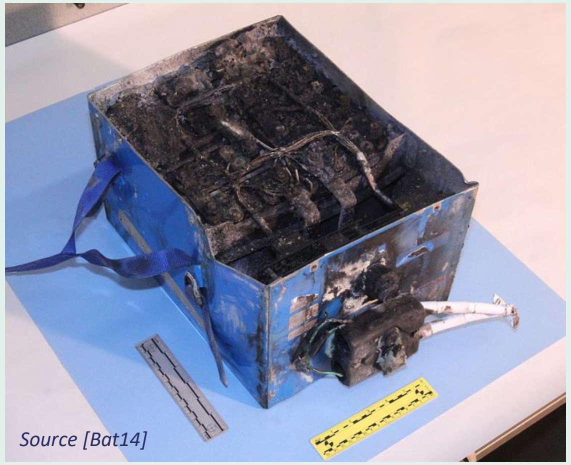
- Electric ➔ short-circuit, overcharge, overdischarge, max current, etc.
- Thermal ➔ high temperature, propagation test, thermal cycling, etc.
- Mechanics ➔ drop, shock, vibrations, impact, crush, etc.

Technical Data

- Cell's internal hot point to start thermal runaway : ~ 90°C (depends on the chemistry)
- Standards: RTCA **DO 311A**



Source [Bat13]



Source [Bat14]

Benefits

-

Drawbacks

-

Synergies

- Mechanical integration in aircraft

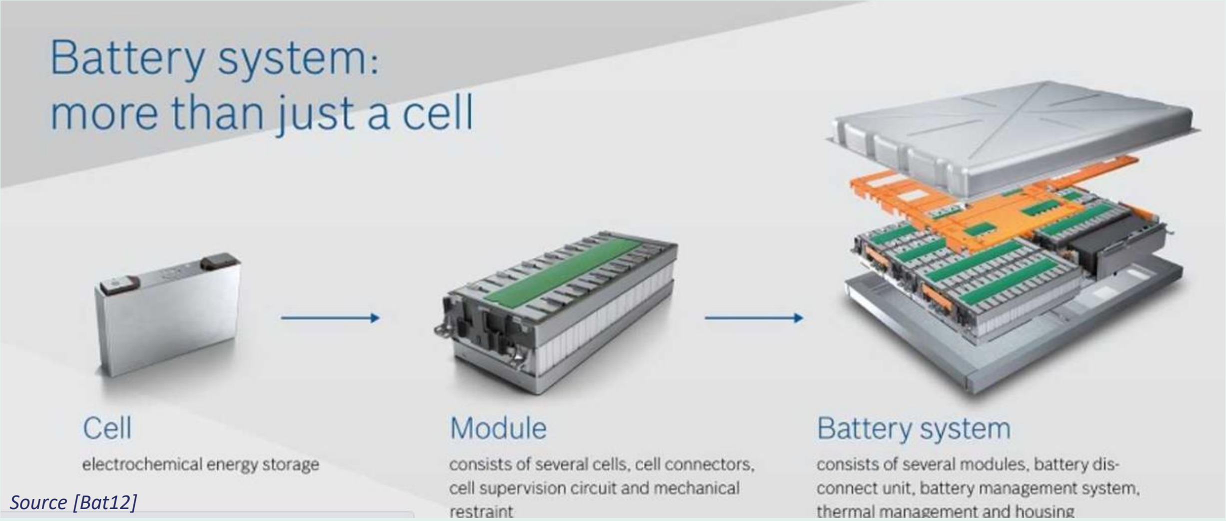
4.4 Battery pack system

Cells are series and parallel assembled into **modules** and then **battery pack**. The battery pack also includes a **BMS** (Battery Management system), a mechanical **housing**, and sometimes a **thermal management system**.

The **BMS** monitors the battery (cells' voltages and temperatures measurements), sends limitations and alerts, balances the cells, calculates the **SOC** (State Of Charge) and the **SOH** (State Of Health). The BMS is generally made of several **electronic boards** that are either connected to modules nor to **power components** such, for instance, contactors and fuses.

The mechanical **housing** is the casing enclosing the battery components and the cells to protect them.

The **thermal management system** , when necessary, cools the battery or heats it.



Source [Bat12]

Technical Data

Examples of battery packs:

	Tesla S 75D	**Dreamliner APU**
Application	Electric vehicle	Aeronautics
Voltage	300 Vnom	30 Vnom
Energy	72 kWh	1,4 kWh
Mass	480 kg	28 kg
Energy density	150 Wh/kg	50 Wh/kg
Housing	Aluminium	Aluminium
Cooling	Water-glycol circuit	No cooling
Number of cells / Electrical architecture	6216 cells / 14 x 6s-74p	8 cells / 8s-1p
Cell	Cylindrical 18650	Prismatic
Chemistry	NCA/graphite	LCO/graphite

Benefits

-

Drawbacks

-

Synergies

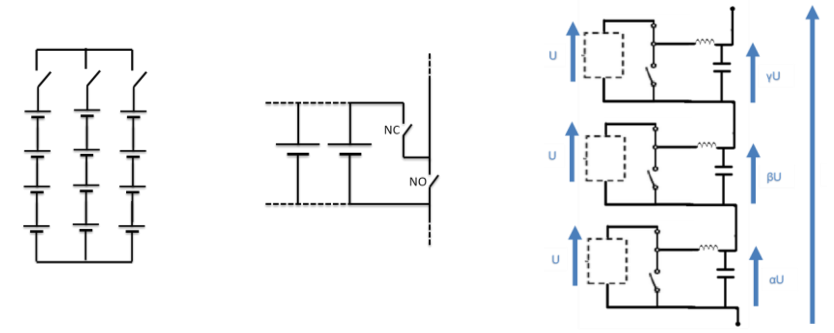
- Mechanical integration in aircraft

4.4 Battery electrical architecture

The battery stores the energy and **delivers or receives energy and power to the systems** (voltage / current) it is interconnected with. It is completely integrated **within the global aircraft electric architecture**.

Inside the battery, the electric architecture defines the **number of cells**, their **series-parallel** connexions, the **electronics** (ex: BMS) and **power electronic components** in the system, the **voltages** and **currents**.

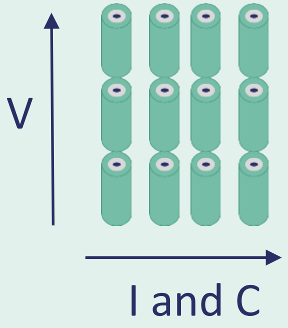
Some prospective architectures use active or passive power devices to increase the **reliability** of the battery pack.



Source CEA LITEN

Electrical architecture solutions to improve battery safety

Technical Data



$E = V*C$

$P = V*I$

Benefits

-

Drawbacks

-

Synergies

- Electrical architecture in aircraft

4.4 Battery thermal management system

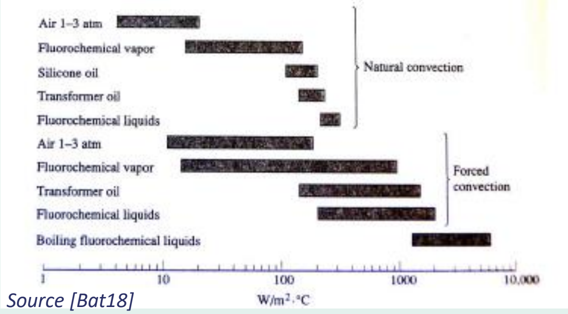
Depending on the application profile and on the constraints on the battery system, a **thermal management system** may be needed for the battery. Thermal management of energy storage is important for:

- **Nominal operation** (min-max T + ΔT; Limit cell's heating especially during continuous charge)
- **Ageing**
- **Safety**

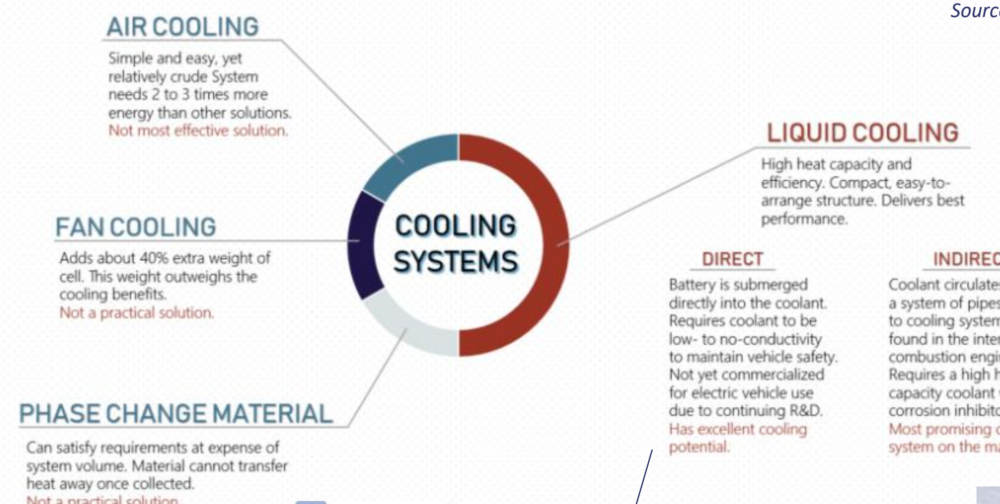
Cooling (/heating) system technologies are various. Most commonly used battery thermal management systems are **air cooling** and **liquid indirect cooling** (ex: with water/glycol or with refrigerant). New solutions such as **direct dielectric** or **phase change materials** are studied in laboratories.

Technical Data

- Typical T range: -40 °C / 60 °C
- Typical efficiency: ˜ 97 % for 2C charge (ex: 10-20 W losses for a 500 W cell)
- Heat transfer coefficient :



Source [Bat18]



Source [Bat15]

AIR COOLING

Simple and easy, yet relatively crude System needs 2 to 3 times more energy than other solutions. Not most effective solution.

FAN COOLING

Adds about 40% extra weight of cell. This weight outweighs the cooling benefits. Not a practical solution.

PHASE CHANGE MATERIAL

Can satisfy requirements at expense of system volume. Material cannot transfer heat away once collected. Not a practical solution.

LIQUID COOLING

High heat capacity and efficiency. Compact, easy-to-arrange structure. Delivers best performance.

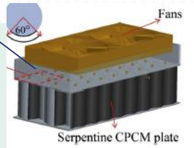
DIRECT

Battery is submerged directly into the coolant. Requires coolant to be low- to no-conductivity to maintain vehicle safety. Not yet commercialized for electric vehicle use due to continuing R&D. Has excellent cooling potential.

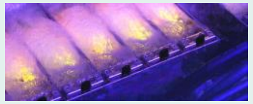
INDIRECT

Coolant circulates through a system of pipes, similar to cooling system currently found in the internal combustion engine. Requires a high heat capacity coolant with corrosion inhibitors. Most promising cooling system on the market.

Source [Bat18]



Source [Bat16]



Source [Bat17]

Source [Bat18]

Benefits

-

Drawbacks

-

Synergies

- Thermal management of the other systems in aircraft

4.4 Battery pack housing

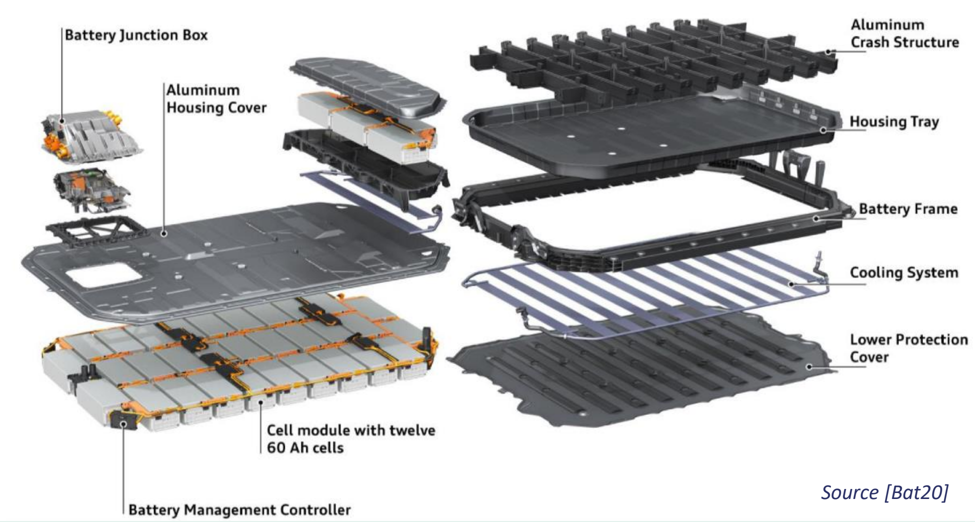
The **mechanical housing** is the envelop around the battery. There can be **one** large housing for the whole battery or **several dispatched** casings per module or per cells.

The **weight ratio casing / battery system** allows us to see the necessary weight needed to pass the D0311A in function of the cells.

The **weight ratio cells / battery system**allows us to see the total mass needed in function of the energy needed.

Technical Data

Weight ratio cells / battery system	**Now day**	**Future**
Automobile	**˜ 55 to 78 %** for a one unique large battery pack.	**˜ 80 %** with battery power density improvement and structural batteries
Aeronautic	**˜ 75-80 %** with most of the time the battery divided in multiple modules. But those batteries **do not fully respect DO311A**	**˜ 75 %** with battery power density improvement and structural batteries and **compliying with the DO311A**



Source [Bat20]

Important fact to take into account :

Aeronautic : the weight part of current casings, which theorically resist to the D0311, is ˜ 50 % to 60 % of the battery system weight, whatever it is aluminium or composite material

Which means, as we want to respect a complete safety of the casing, a large amount of the mass on the casing is required to pass the DO311A.

This will directly change the ratio cells/battery as a bigger amount of weight will be needed for the casing. And so decrease the ratio cell/battery.

4.4 Battery mechanical integration: composite

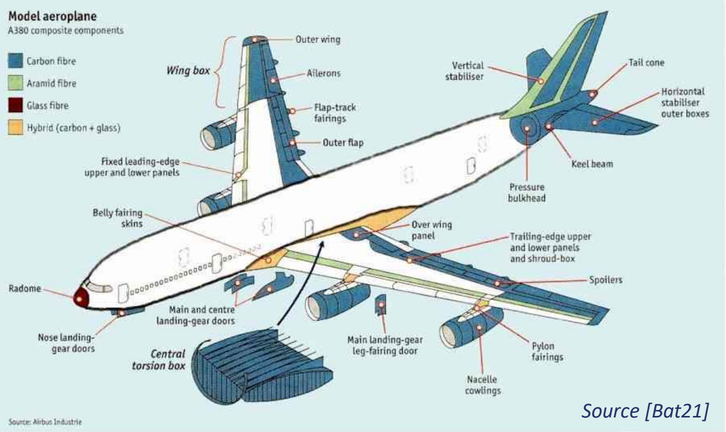
A **composite** material is an assembly of at least two immiscible components (but having a high penetration capacity) whose properties complement each other. The new material thus formed, heterogeneous, has properties that the components alone do not have.

The constant evolution of composite material's world bring more and more solutions of conception for aircraft.

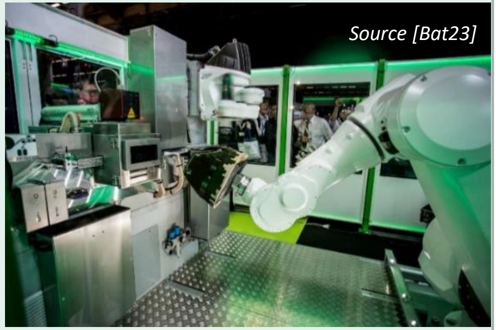
Nanoparticles are also a new source for improving the properties of composite materials. Many nanoparticles are still being studied, but some such as graphene seem promising and will be able to bring real gain to composite materials (improvement of conductivity, strenght).

Technical Data

- Automatisation of production (SOVOTEC picture), this future technology will reduce waste, scrap parts and price of fabrication
- 3D printing of thermoplastic high module (PEEK, PEKK) show us that thermoplastic is growing up and can be helpfull for battery casing.
- The growing up of thermoplastic in the near future will allow better recycleability of product and even reshaping of them.
- 3D printing offers to print composite materials in one direction, but in the future printing a complex weaving should be possible.
- Composite carbon already exists in battery casing and is already an interesting alternative.



Source [Bat21]



Source [Bat23]

Source [Bat22]

Benefits/Synergies

- Evolution of composite will allow us to have easier access to it to build complex shape
- Additives promise a good future for the customization of composites (nanoparticles cooling in the sun, insulating nanoparticles, reinforcing fireproof)
- Combine with 3D printing, composite can become easy to produce in automatic version
- Evolution of thermoplastic will make composite material more and more recyclable

Drawbacks

- We have no idea if the price will decrease or stay high.
- The infinite possibilities of conception and fabrication make it difficult to find the right composite for the right application.

4.4 Battery mechanical integration: 3D printing

Parts produced by **additive layer manufacturing (ALM)**, also known as **3D printing**, In September 2017, following thorough testing and EASA approval, the first titanium 3D-printed part was installed on a serial production aircraft (AIRBUS).

In addition to its potential for decarbonisation, 3D printing is an essential technology for the digitalization of industry. One of the advantages is that new parts can be virtually designed, printed on site and then tested – all in a very short timespan. This allows a better mastering of the technology against failure.

Technical Data

- ALM can **reduce the weight up to 55 % less,** while reducing raw material used by up to 90 % (AIRBUS).
- Processing superalloys is also more cost-effective with 3D printing, since the material usage rate is lower. The results: significantly reduced environmental pollution over the lifetime of the aircraft (AIRBUS).
- The **realization of a high-pressure hydraulic valve block using EOS metal 3D printin**g technology marks an important milestone. This valve block has been tested on a flight with an Airbus A380 aircraft. This means that 3D printing material can be successful for mechanical/structural parts.


Source [Bat24]


Source [Bat24]

Benefits/Synergies

- **Lower weight** for the casing
- Capacity to **integrate functions** with the modularity of 3D printing
- **Reduce number of pieces** product
- **Reduce waste** and environmental pollution

Drawbacks

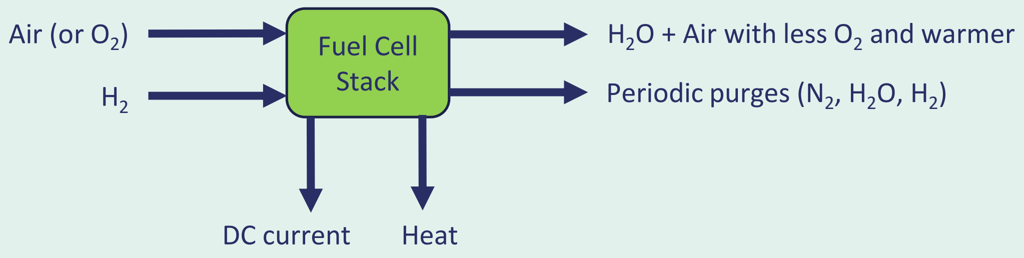
- Time of printing is long
- 3D printing exist for composite, but it is currently limited by the technology of printing which locked the weaving in one option

4.4 Battery housing with new material or process (composite, 3Dprinting)

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] ✓	>7	
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% ✓	
Design tools Maturity TODAY	In house academy ✓	General Available	Commercial	
A/C level impact : integration synergy potential		✓		
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23 ✓	Special Condition CS23 / CS 25	
Consortium Experience TODAY	✓			
Maturity for circular economy / Life Cycle @ EIS	✓			Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect ✓	Direct	High	
Operations impact	No change	Medium ✓	Paradigm Shift	
Complexity	No change / Minor Increase ✓	Medium Increase	High Increase	
Price Point	No change / Minor Increase	Medium Increase	High Increase	

4.5 Fuel cell principle and technologies

$H_2 + ½\,O_2 \rightarrow H_2O$ + electricity + heat



Air (or O_2)

H_2

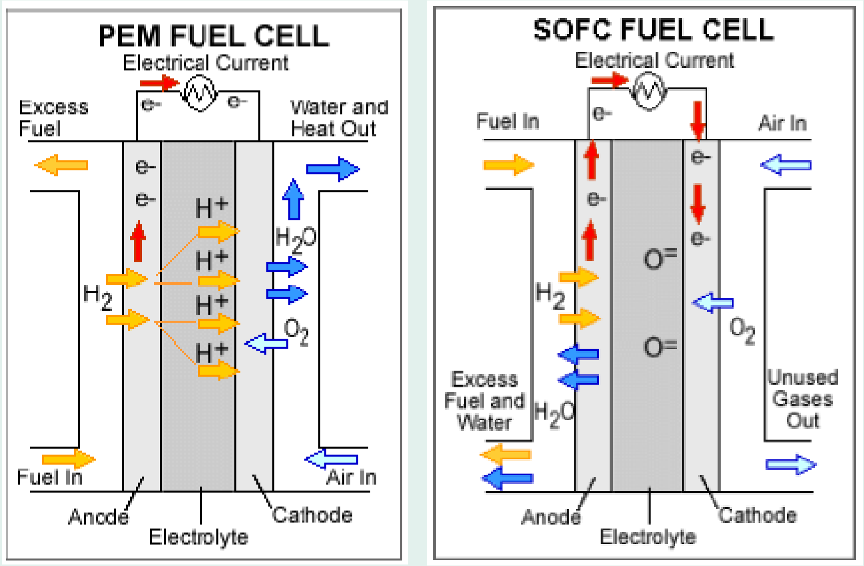
Fuel Cell Stack

H_2O + Air with less O_2 and warmer

Periodic purges (N_2, H_2O, H_2)

DC current

Heat



Source: DOE Multi-Year Research, Development and Demonstration (MYRD&D) Plan, 2016

Technical Data

- **LT-PEMFC**: stack temperature = 60-80°C, technology used in commercial automotive applications (mature technology), but expensive catalyst (Pt), sensitivity to pollutants (CO…)
- **MT-PEMFC**: stack temperature = 90-120°C, less sensitivity to pollutants like CO…, but maturity & durability < LT-PEMFC
- **HT-PEMFC**: stack temperature = 120-180°C, no water management required, low sensitivity to pollutants like CO…, but specific power, maturity & durability < LT-PEMFC
- **SOFC**: stack temperature = 550-1000°C, non precious catalyst material, low sensitivity to pollutants like CO…, fuel = H2 or hydrocarbons (CH4, kerosene…) directly at anode inlet or with an additionnal reformer before anode inlet

FC stack temperature ↗

Size of cooling system ↘

Energy generation from heat ↗

➢ Best option today for aeronautics seems to be **LT-PEMFC** thanks to its higher maturity and its high specific power

Benefits/Synergies

- high energy gravimetric density of hydrogen

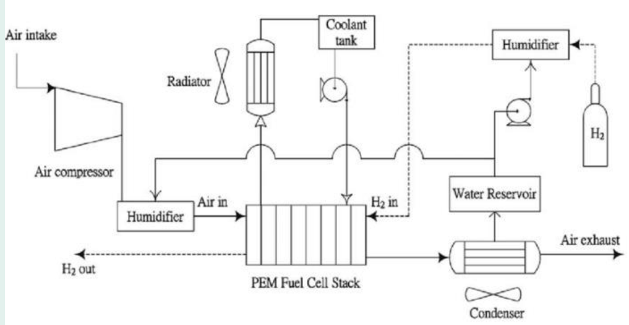
Drawbacks

- complex system
- H2 storage

4.5 Fuel cell system and specific power (PEMFC LT)

Fuel Cell System includes Fuel Cell Stack + Balance of Plant (BOP)

- Air path
- Hydrogen path
- Cooling path
- Monitoring & Control
- (Power electronics)



Source: Ultrasonic Spray Coating for Proton Exchange Membrane Fuel Cell, Jao et al., Open Journal of Acoustics, 2013, 3, 33-37

Technical Data

Automotive 80 kWe PEMFC system specific power roadmap :
- State of the art = 650 W/kg (DOE, FCTT Roadmap 2017)
- 2025 Target = **900 W/kg** (FCTT Roadmap 2017)
(includes fuel cell stack, BOP, thermal system; excludes H2 storage, battery, power electronics, electric drive).
- 2040 Target = ???

Aeronautics PEMFC system specific power roadmap :
- State of the art = 750 W/kg
- 2025-2030: **1700-2000 W/kg** (2 to 3 times higher than current PEMFC systems)

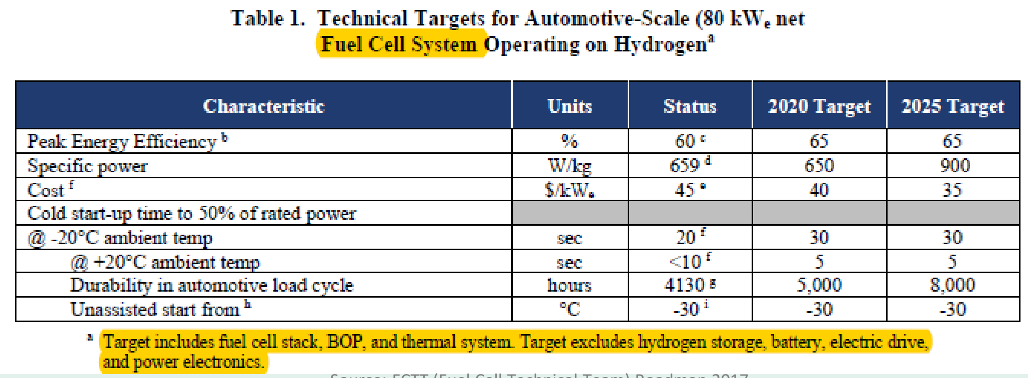
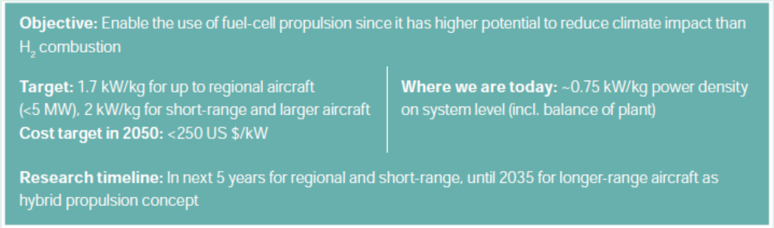


Table 1. Technical Targets for Automotive-Scale (80 kW$_e$ net Fuel Cell System Operating on Hydrogen[a]

Characteristic	Units	Status	2020 Target	2025 Target
Peak Energy Efficiency [b]	%	60 [c]	65	65
Specific power	W/kg	659 [d]	650	900
Cost [f]	\$/kW$_e$	45 [e]	40	35
Cold start-up time to 50% of rated power				
@ -20°C ambient temp	sec	20 [f]	30	30
@ +20°C ambient temp	sec	<10 [f]	5	5
Durability in automotive load cycle	hours	4130 [g]	5,000	8,000
Unassisted start from [h]	°C	-30 [i]	-30	-30

[a] Target includes fuel cell stack, BOP, and thermal system. Target excludes hydrogen storage, battery, electric drive, and power electronics.

Source: FCTT (Fuel Cell Technical Team) Roadmap 2017



Objective: Enable the use of fuel-cell propulsion since it has higher potential to reduce climate impact than H_2 combustion

Target: 1.7 kW/kg for up to regional aircraft (<5 MW), 2 kW/kg for short-range and larger aircraft
Cost target in 2050: <250 US $/kW

Where we are today: ~0.75 kW/kg power density on system level (incl. balance of plant)

Research timeline: In next 5 years for regional and short-range, until 2035 for longer-range aircraft as hybrid propulsion concept

Source: Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050, 2020 (https://www.cleansky.eu/sites/default/files/inline-files/20200507_Hydrogen-Powered-Aviation-report.pdf)

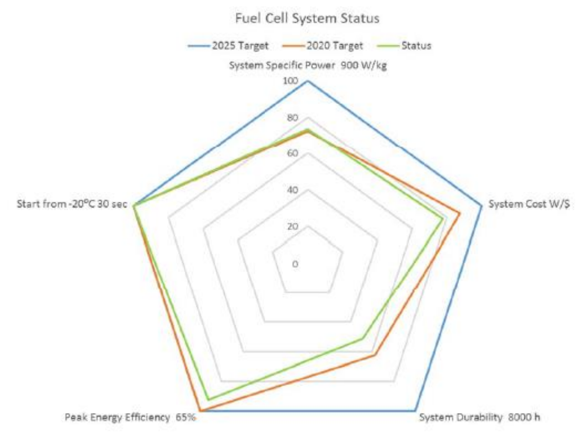


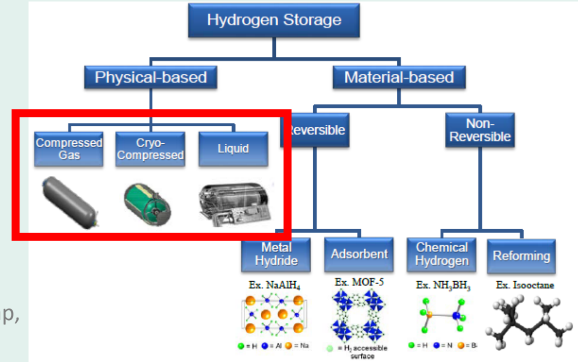
Figure 1. Fuel Cell System Status versus Targets
(The green line indicates the status as a fraction of the targets)

Source: FCTT (Fuel Cell Technical Team) Roadmap 2017

4.6 Hydrogen storage

Many H2 storage technologies with different maturities, specs and ease of use. Physical-based storages are currently the most considered options

- **CGH2**: Compressed Gaseous Hydrogen (typically 350 bar or 700 bar, ambiant temperature)
- **Cold compressed H2** (cooled H2 gas delivered from station)
- **CcH2**: Cryo-compressed Hydrogen (up to 1000 bar, 33-73 K) (liquid H2 delivered from station)
- **LH2**: Liquid Hydrogen (~1-4 bar, 20 K).
- …

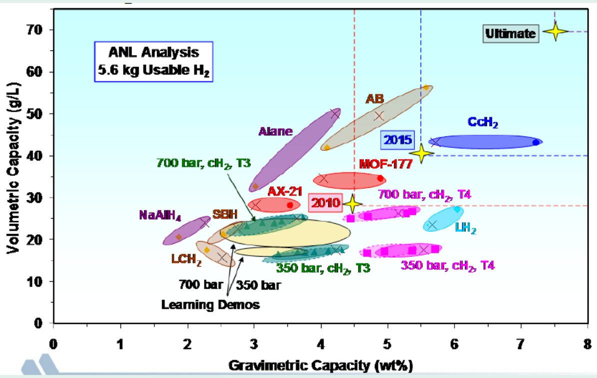


Source: Hydrogen Storage Tech Team (HSTT) Roadmap, July 2017, US DRIVE

Technical Data

- Hydrogen alone (without tank) is the fuel with the highest energy gravimetric density (Low Heating Value « LHV » = 120 MJ/kg)
- But Hydrogen requires more volume than other fuels .

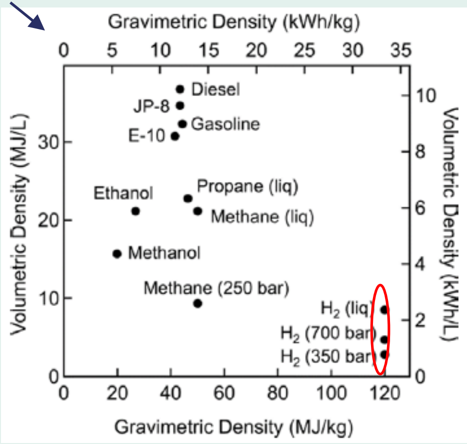
Gravimetric index = weight of H2 / weight of tank full with H2



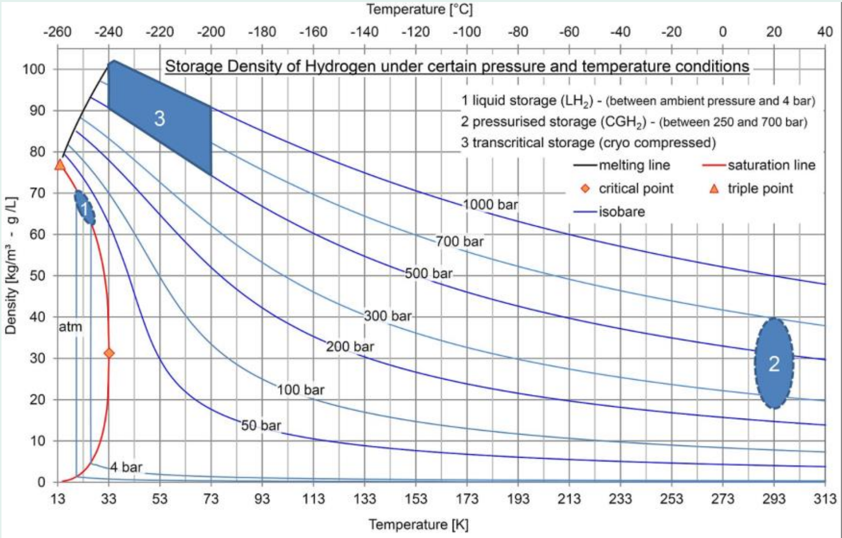
Source: Ahluwalia et al., Cryo-Compressed Hydrogen Storage: Performance and Cost Review, Argonne National Lab, 2011

- Diagram to be regarded as a snapshot in time
- Different systems not analyzed to same level of sophistication
- Advanced materials not ready for deployment
- Some component concepts require further development

kWh and MJ refer to LHV



Source: Hydrogen Storage Tech Team (HSTT) Roadmap, July 2017, US DRIVE

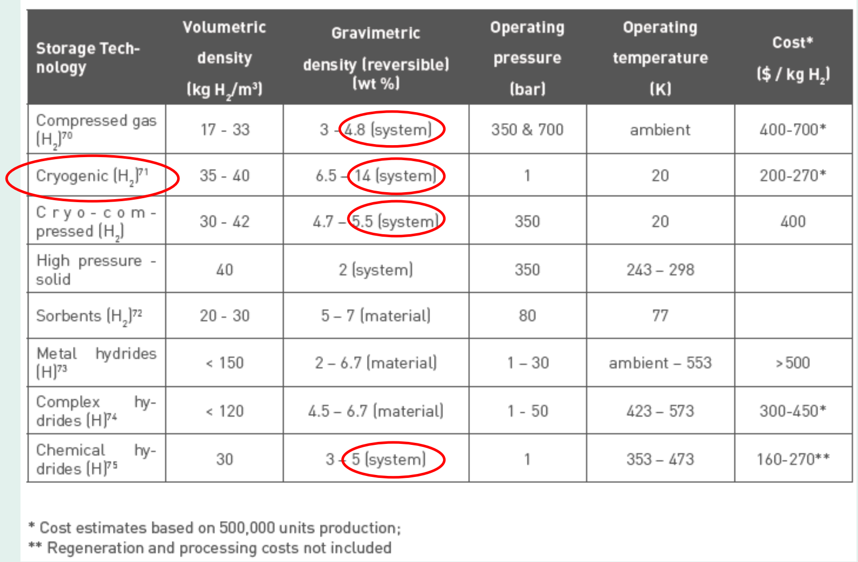


Source: https://www.ilkdresden.de/en/service/research-and-development/project/hydrogen-test-area-at-ilk-dresden/

4.6 Hydrogen storage: specific energy with storage system (kWh H2/kg sys or kg H2/kg sys)

SET-Plan Targets for Hydrogen Storage Technologies for 2030 and beyond

- LH2 expected to be much ligther (14 %wt) than other H2 storage technologies
- Table is oriented for **stationary applications** (higher %wt for mobile apps?)



Storage Technology	Volumetric density (kg H_2/m^3)	Gravimetric density (reversible) (wt %)	Operating pressure (bar)	Operating temperature (K)	Cost* ($ / kg H_2)
Compressed gas (H_2)[70]	17 - 33	3 - 4.8 (system)	350 & 700	ambient	400-700*
Cryogenic (H_2)[71]	35 - 40	6.5 – 14 (system)	1	20	200-270*
Cryo-compressed (H_2)	30 - 42	4.7 – 5.5 (system)	350	20	400
High pressure - solid	40	2 (system)	350	243 – 298	
Sorbents (H_2)[72]	20 - 30	5 – 7 (material)	80	77	
Metal hydrides (H)[73]	< 150	2 – 6.7 (material)	1 – 30	ambient – 553	>500
Complex hydrides (H)[74]	< 120	4.5 – 6.7 (material)	1 - 50	423 – 573	300-450*
Chemical hydrides (H)[75]	30	3 - 5 (system)	1	353 – 473	160-270**

* Cost estimates based on 500,000 units production;
** Regeneration and processing costs not included

Source: EASE-EERA European Energy Storage Technology Development Roadmap, 2017 Update (p. 52)
SET Plan : European Strategic Energy Technology Plan

kWh refers to LHV

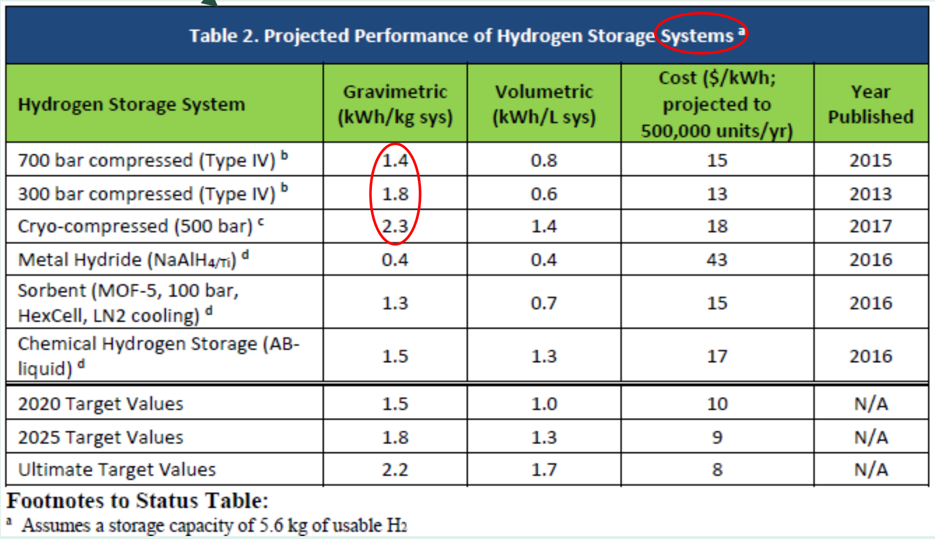


Table 2. Projected Performance of Hydrogen Storage Systems [a]

Hydrogen Storage System	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Cost ($/kWh; projected to 500,000 units/yr)	Year Published
700 bar compressed (Type IV) [b]	1.4	0.8	15	2015
300 bar compressed (Type IV) [b]	1.8	0.6	13	2013
Cryo-compressed (500 bar) [c]	2.3	1.4	18	2017
Metal Hydride ($NaAlH_{4/Ti}$) [d]	0.4	0.4	43	2016
Sorbent (MOF-5, 100 bar, HexCell, LN2 cooling) [d]	1.3	0.7	15	2016
Chemical Hydrogen Storage (AB-liquid) [d]	1.5	1.3	17	2016
2020 Target Values	1.5	1.0	10	N/A
2025 Target Values	1.8	1.3	9	N/A
Ultimate Target Values	2.2	1.7	8	N/A

Footnotes to Status Table:

[a] Assumes a storage capacity of 5.6 kg of usable H_2

Source: HSTT (Hydrogen Storage Technical Team) Roadmap 2017

Technical Data

- For LH2, mass of tank is very dependent on the H2 consumption profile and the resulting boil-off, and on safety requirements → trade-off between weight of thermal insulation and boil-off management vs loss of H2, and mechanical stability
- Expected weight for planes : LH2 < CcH2 < CGH2 300 bar < CGH2 700 bar

4.6 Hydrogen storage: specific energy roadmap

Automotive H2 storage system roadmap :

For automotive 5,6 kg usable H2 storage system, all technologies (CGH2, LH2, hydrides…) (expected to be lighter with a higher H2 quantity since H2 systems = fixed & scalable elements) (includes everything: tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and all other balance-of-plant components.
Capacities are defined as the usable quantity of hydrogen deliverable to the fuel cell system divided by the total mass/volume of the complete storage system, including all stored hydrogen, media, reactants. Values at end of service life.

(kWh refers to LHV)

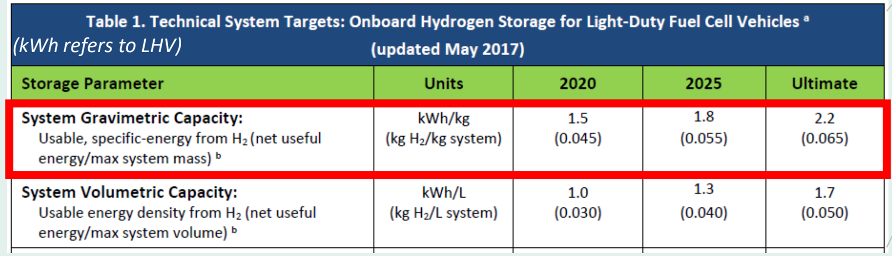


Table 1. Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles [a] (updated May 2017)

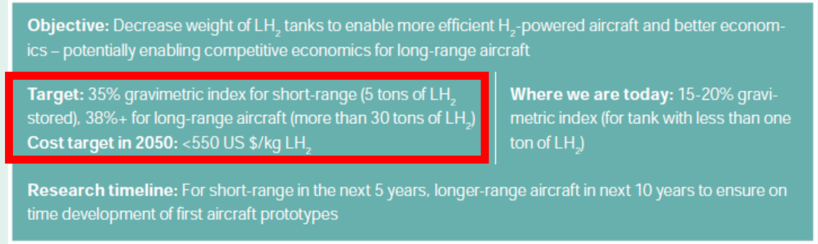
Storage Parameter	Units	2020	2025	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass) [b]	kWh/kg (kg H_2/kg system)	1.5 (0.045)	1.8 (0.055)	2.2 (0.065)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L (kg H_2/L system)	1.0 (0.030)	1.3 (0.040)	1.7 (0.050)

Source: HSTT (Hydrogen Storage Technical Team) Roadmap 2017

Toyota Mirai 2014 : 4.7 kg useable H2 capacity, 108 kg → 4,35 %wt (source HSTT 2017)
Automotive specs = conservative for planes (LH2 not considered for automotive).

Aeronautics LH2 storage system roadmap :

Gravimetric index = weight of LH2 / weight of tank full with LH2
Current prototypes = 0,15-0,20 kg_H2/kg_system = 20 %wt
2025-2030: **0,35-0,38 kg_H2/kg_system = 35-38 %wt**



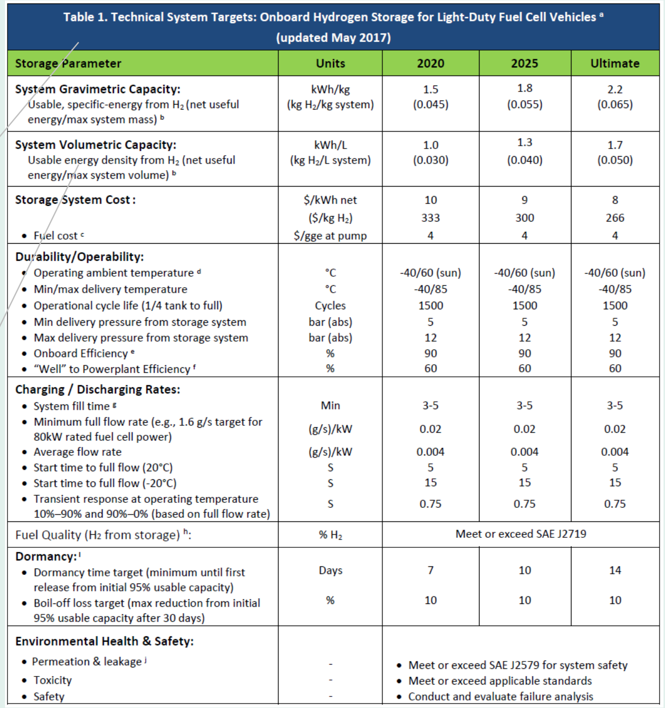
Objective: Decrease weight of LH_2 tanks to enable more efficient H_2-powered aircraft and better economics – potentially enabling competitive economics for long-range aircraft

Target: 35% gravimetric index for short-range (5 tons of LH_2 stored), 38%+ for long-range aircraft (more than 30 tons of LH_2)
Cost target in 2050: <550 US $/kg LH_2

Where we are today: 15-20% gravimetric index (for tank with less than one ton of LH_2)

Research timeline: For short-range in the next 5 years, longer-range aircraft in next 10 years to ensure on time development of first aircraft prototypes

Source: Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050, 2020 (https://www.cleansky.eu/sites/default/files/inline-files/20200507_Hydrogen-Powered-Aviation-report.pdf)



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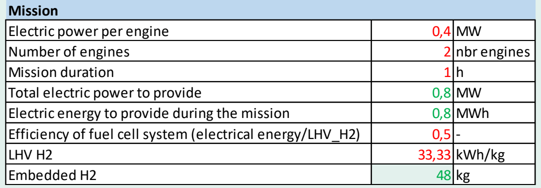
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume) [b]	kWh/L (kg H_2/L system)	1.0 (0.030)	1.3 (0.040)	1.7 (0.050)
Storage System Cost :	$/kWh net ($/kg H_2)	10 333	9 300	8 266
• Fuel cost [c]	$/gge at pump	4	4	4
Durability/Operability:				
• Operating ambient temperature [d]	°C	-40/60 (sun)	-40/60 (sun)	-40/60 (sun)
• Min/max delivery temperature	°C	-40/85	-40/85	-40/85
• Operational cycle life (1/4 tank to full)	Cycles	1500	1500	1500
• Min delivery pressure from storage system	bar (abs)	5	5	5
• Max delivery pressure from storage system	bar (abs)	12	12	12
• Onboard Efficiency [e]	%	90	90	90
• "Well" to Powerplant Efficiency [f]	%	60	60	60
Charging / Discharging Rates:				
• System fill time [g]	Min	3-5	3-5	3-5
• Minimum full flow rate (e.g., 1.6 g/s target for 80kW rated fuel cell power)	(g/s)/kW	0.02	0.02	0.02
• Average flow rate	(g/s)/kW	0.004	0.004	0.004
• Start time to full flow (20°C)	S	5	5	5
• Start time to full flow (-20°C)	S	15	15	15
• Transient response at operating temperature 10%–90% and 90%–0% (based on full flow rate)	S	0.75	0.75	0.75
Fuel Quality (H_2 from storage) [h]:	% H_2	Meet or exceed SAE J2719		
Dormancy: [i]				
• Dormancy time target (minimum until first release from initial 95% usable capacity)	Days	7	10	14
• Boil-off loss target (max reduction from initial 95% usable capacity after 30 days)	%	10	10	10
Environmental Health & Safety:				
• Permeation & leakage [j]	-	• Meet or exceed SAE J2579 for system safety		
• Toxicity	-	• Meet or exceed applicable standards		
• Safety	-	• Conduct and evaluate failure analysis		

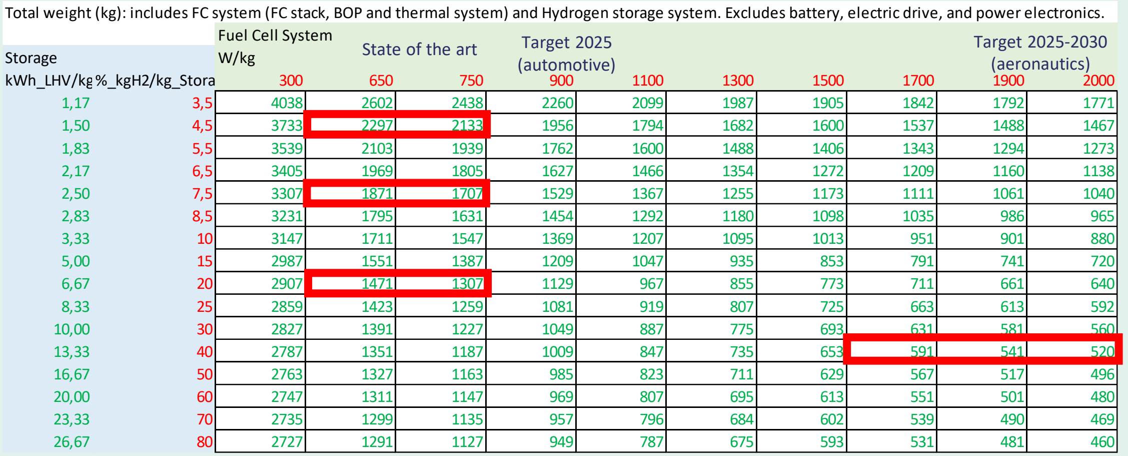
4.7 100% Fuel Cell solution (overall weight and overall Wh net/kg)

Assumptions for calculation = preliminary Futprint data:



Mission		
Electric power per engine	0,4	MW
Number of engines	2	nbr engines
Mission duration	1	h
Total electric power to provide	0,8	MW
Electric energy to provide during the mission	0,8	MWh
Efficiency of fuel cell system (electrical energy/LHV_H2)	0,5	-
LHV H2	33,33	kWh/kg
Embedded H2	48	kg

Weight of FC system + H2 storage with automotive technology

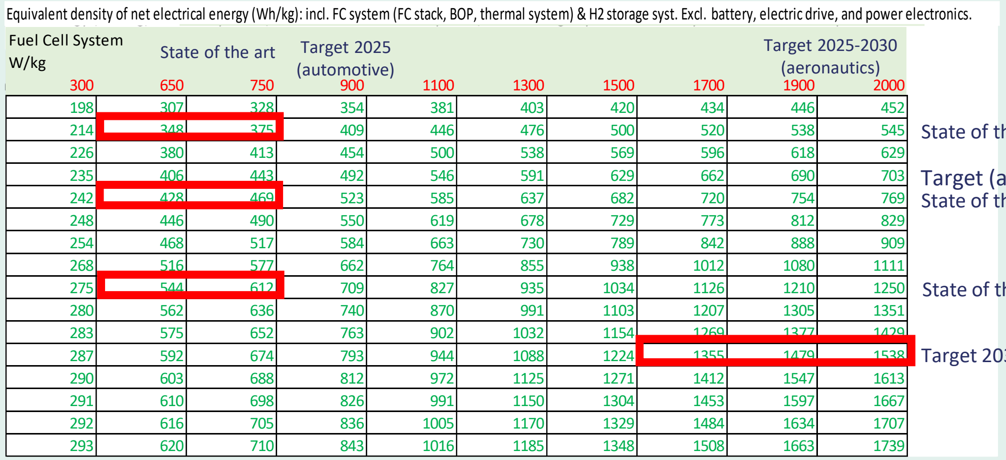


Total weight (kg): includes FC system (FC stack, BOP and thermal system) and Hydrogen storage system. Excludes battery, electric drive, and power electronics.

Storage		Fuel Cell System W/kg	State of the art		Target 2025 (automotive)					Target 2025-2030 (aeronautics)	
kWh_LHV/kg	%_kgH2/kg_Stora	300	650	750	900	1100	1300	1500	1700	1900	2000
1,17	3,5	4038	2602	2438	2260	2099	1987	1905	1842	1792	1771
1,50	4,5	3733	2297	2133	1956	1794	1682	1600	1537	1488	1467
1,83	5,5	3539	2103	1939	1762	1600	1488	1406	1343	1294	1273
2,17	6,5	3405	1969	1805	1627	1466	1354	1272	1209	1160	1138
2,50	7,5	3307	1871	1707	1529	1367	1255	1173	1111	1061	1040
2,83	8,5	3231	1795	1631	1454	1292	1180	1098	1035	986	965
3,33	10	3147	1711	1547	1369	1207	1095	1013	951	901	880
5,00	15	2987	1551	1387	1209	1047	935	853	791	741	720
6,67	20	2907	1471	1307	1129	967	855	773	711	661	640
8,33	25	2859	1423	1259	1081	919	807	725	663	613	592
10,00	30	2827	1391	1227	1049	887	775	693	631	581	560
13,33	40	2787	1351	1187	1009	847	735	653	591	541	520
16,67	50	2763	1327	1163	985	823	711	629	567	517	496
20,00	60	2747	1311	1147	969	807	695	613	551	501	480
23,33	70	2735	1299	1135	957	796	684	602	539	490	469
26,67	80	2727	1291	1127	949	787	675	593	531	481	460

Equivalent net energy density of FC system + H2 storage system

= net electrical energy available at Fuel Cell system output / (weight of FC system + H2 storage system)



Equivalent density of net electrical energy (Wh/kg): incl. FC system (FC stack, BOP, thermal system) & H2 storage syst. Excl. battery, electric drive, and power electronics.

Fuel Cell System W/kg	State of the art		Target 2025 (automotive)					Target 2025-2030 (aeronautics)		
300	650	750	900	1100	1300	1500	1700	1900	2000	
198	307	328	354	381	403	420	434	446	452	
214	348	375	409	446	476	500	520	538	545	State of the art (automotive CGH2)
226	380	413	454	500	538	569	596	618	629	
235	406	443	492	546	591	629	662	690	703	Target (automotive)
242	428	469	523	585	637	682	720	754	769	State of the art 2011 CcH2
248	446	490	550	619	678	729	773	812	829	
254	468	517	584	663	730	789	842	888	909	
268	516	577	662	764	855	938	1012	1080	1111	
275	544	612	709	827	935	1034	1126	1210	1250	State of the art (LH2 aeronautics)
280	562	636	740	870	991	1103	1207	1305	1351	
283	575	652	763	902	1032	1154	1269	1377	1429	
287	592	674	793	944	1088	1224	1355	1479	1538	Target 2030 (LH2 aeronautics)
290	603	688	812	972	1125	1271	1412	1547	1613	
291	610	698	826	991	1150	1304	1453	1597	1667	
292	616	705	836	1005	1170	1329	1484	1634	1707	
293	620	710	843	1016	1185	1348	1508	1663	1739	

➔ State of the art CGH2 automotive : 350 Wh net/kg sys

➔ State of the art LH2 aeronautics : 610 Wh net/kg sys

➔ Target 2030 LH2 aeronautics : 1300-1500+ Wh net/kg sys

(These results depends on mission's profile : Electric energy to provide ~ weight of H2 storage (longer flight → weight savings of H2 ↗) + Max power to provide ~ weight of Fuel Cell System
If peak power required for short duration → hybridization Fuel Cell + Battery to save weight on FC)

4.8 Hydrogen: integration in planes

- Hydrogen can be used with **different energy conversion technologies**:
  - Turbojet engines (standard for big planes)
  - Internal Combustion Engines (standard for small planes)
  - Turbine + electric generator + electric motors
  - PEM Fuel Cells
  - Solid Oxid Fuel Cells
  - …

- Hydrogen was already used succesfully in test flights. Hydrogen in planes and aeronautics is **not new.**
  - Tupolev TU-155 in 1988
  - Boeing Fuel Cell Demonstrator, 2008 (Diamond HK36 Super Dimona motor glider airframe + Fuel Cell)
  - Antares DLR-H2, 2009, 2012 (2-5 kg CGH2 + 33 kW Fuel Cell)
  - Hy4 / MAHEPA project
  - Airbus A320-232 ATRA with 25 kW PEMFC (DLR + Michelin + Airbus, 2008) to replace RAT (Ram Air Turbine) + APU
  - UAVs
  - JCH JU / HYCARUS project (Safran, CEA, Dassault, etc) with Fuel cell in cabin (TRL6), 2013

- **Danger** with hydrogen **is different** than danger with kerosen.

Pictures

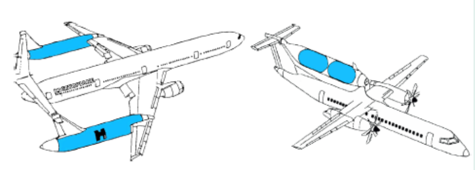


Fig. 14. Twin tail-boom and tail-tank concepts [23].

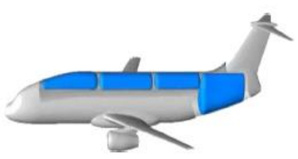


Fig. 8. Integral tank [18].

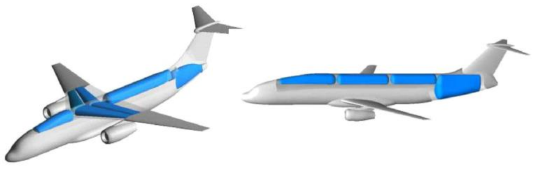


Fig. 15. Hydrogen aircraft with different hydrogen tank configurations [18].

Source: Khandelwal et al., Hydrogen powered aircraft : The future of air transport, Progress in Aerospace Sciences, 2013

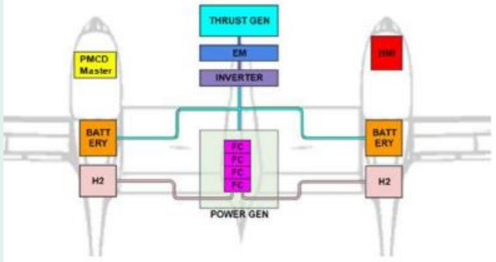


Figure 6: A MAHEPA serial FC- hybrid drivetrain architecture

Source: MAHEPA project, 2019.

Source: Airbus, 2020

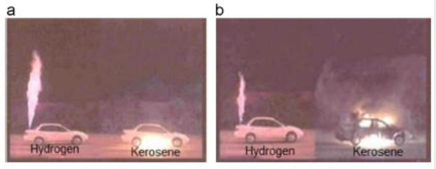


Fig. 23. Flammability comparison of hydrogen and kerosene [54].

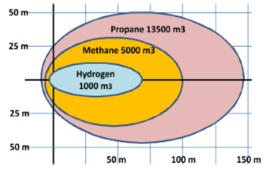


Fig. 24. Danger zone of spilled liquid gas [55].

Source: Khandelwal et al., Hydrogen powered aircraft : The future of air transport, Progress in Aerospace Sciences, 2013

4.8 Hydrogen: synergies

Possible synergies planes + PEMFC:

- Electricity (Taxi / On board equipments, network / Electrical main engine start / Others?)
- Heat (De-icing / Hot water / Galley (meals) / Others?)
- Water (Air humidification system (cabin air) / Potable water / Water for toilets / Water injection in engine / Others?)
- O2 depleted air (Inerting of kerosene tanks / Inerting of e-bay compartments, cargo… / Others?)

Possible synergies planes + LH2 / CcH2:

- Cooling (LH2 and CcH2 to a lesser extent for embedded cooling: latent heat of LH2 = 440 kJ/kg)
- Reliability of electrical parts
- Weight savings of electrical parts
- Others?

Hybridization?

Kerosene? + Battery?
Kerosene? + Battery? + Supercap/LiC?
Kerosene? + Battery? + Fuel Cell? + H2 gas or liq?
Kerosene? + Fuel Cell? + H2 gas or liq? (+ Small start-up battery?)
Kerosene? + H2 gas or liq?

Pictures

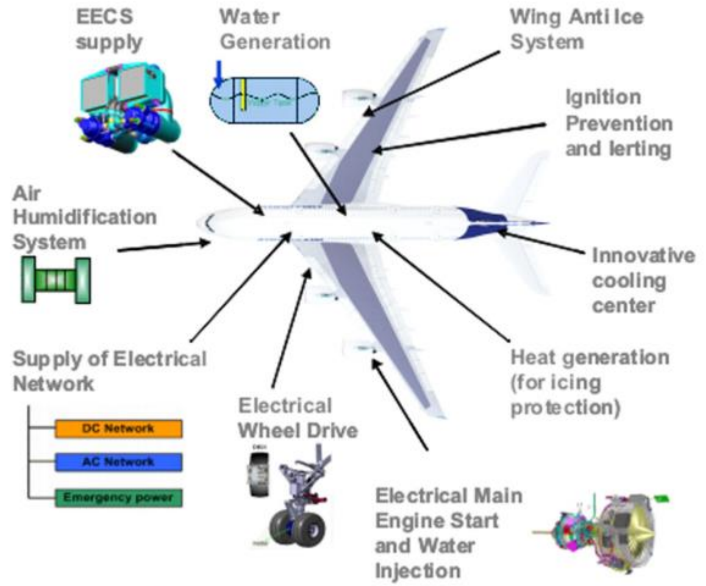


Figure 2: **Multifunctional fuel cell system: The possible functions are power supply, emission free ground operation, electrical main engine start, electrical environmental control system (EECS), water generation (potable water and water for toilets), heat generation (icing prevention, hot water generation), explosion and fire prevention and suppression (inerting of tanks, cargo and e-bay compartment), cockpit and / or cabin air humidification.**

Source: Kallo et al., Fuel Cell System Development and Testing for Aircraft Applications, Proceedings of the WHEC, May 16.-21. 2010, Essen

4.5- 4.6 Fuel cell and H2

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] ✓	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% ✓	Why?
Design tools Maturity TODAY	In house academy ✓	General Available	Commercial	
A/C level impact : integration synergy potential			✓	(w/ which systems?)
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23 ✓	Special Condition CS23 / CS 25	
Consortium Experience TODAY			✓	What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS		✓		Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High ✓	Which emissions?
Operations impact	No change	Medium	Paradigm Shift ✓	
Complexity	No change / Minor Increase	Medium Increase	High Increase ✓	Why? What parts?
Price Point	No change / Minor Increase	Medium Increase	High Increase	Why? What material needed? Etc.

4 Energy storage

References for figures:

REF	Weblink
[Bat1]	http://www.theses.fr/2019BORD0029
[Bat2]	https://www.youtube.com/watch?v=VxMM4g2Sk8U
[Bat3]	https://ecodesignbatteries.eu/files/attachments/ED_Battery_Task%201_V16.pdf
[Bat4]	https://eduscol.education.fr/sti/sites/eduscol.education.fr.sti/files/ressources/pedagogiques/12098/12098-etat-de-lart-et-perspectives-des-batteries-de-ve-ensps.pdf
[Bat5]	https://www.jmenergy.co.jp/en/lithium_ion_capacitor/
[Bat6]	https://battery2030.eu/digitalAssets/860/c_860904-l_1-k_roadmap-27-march.pdf
[Bat7]	https://www.mst.or.jp/portals/0/prize/english/winners/material/material2018_en.html
[Bat8]	https://asia.nikkei.com/Business/Technology/New-battery-technologies-still-years-away
[Bat9]	https://oxisenergy.com/products/
[Bat10]	https://onlinelibrary.wiley.com/doi/full/10.1002/anie.200705648
[Bat11]	https://www.researchgate.net/publication/264500119_Quantifying_the_promise_of_lithium-air_batteries_for_electric_vehicles
[Bat12]	https://insideevs.com/news/334935/bosch-disbands-internal-battery-cell-research-will-sell-solid-state-startup-seeo/
[Bat13]	https://www.sciencedirect.com/topics/chemistry/thermal-runaway
[Bat14]	https://en.wikipedia.org/wiki/Boeing_787_Dreamliner_battery_problems#/media/File:1-7-12_JAL787_APU_Battery.JPG
[Bat15]	https://www.dober.com/electric-vehicle-cooling-systems#electric_vehicle_cooling_systems
[Bat16]	https://www.sciencedirect.com/science/article/pii/S0378775320307023
[Bat17]	https://www.3mfrance.fr/3M/fr_FR/novec-fr/applications/refroidissement-par-immersion/
[Bat18]	https://everlasting-project.eu/wp-content/uploads/2020/02/EVERLASTING_D8.14_final_20200224.pdf
[Bat19]	https://bli5.lbl.gov/2012/03/28/dr-tom-greszler/#more-1646
[Bat20]	https://www.greencarreports.com/news/1116347_audi-details-battery-for-2019-e-tron-electric-suv
[Bat21]	https://images.app.goo.gl/r6ZUYBefoyYPijhJ6
[Bat22]	https://www.3dnatives.com/impression-3d-composite-28012020/
[Bat23]	https://www.techniques-ingenieur.fr/actualite/articles/cevotec-automatise-la-fabrication-de-pieces-en-fibres-composites-67494/
[Bat24]	https://www.techniques-ingenieur.fr/res/pdf/encyclopedia/42632210-bm7940.pdf
[Bat25]	https://iopscience.iop.org/article/10.1088/2399-7532/ab3bdd/pdf

4 Energy storage

Bibliography 1/4:

Item	Year	Author or ENTITY	Title
Battery roadmap	2020	BATTERY 2030 consortium	Battery 2030+
Battery roadmap	2013	FRAUNHOFER	Technology Roadmap Energy storage for Electric mobility 2030
Battery roadmap	2019	EUCAR	Battery requirements for future automotive applications EG BEV&FCEV
Battery roadmap	2018	D. Little Arthur	Future of batteries
Battery roadmap	2017	EASA-EERA	EASE-EERA-Storage-Technology-Development-Roadmap-2017-HR
Battery roadmap	2018	European Commission	Towards the battery of the future – Futur brief 20
Hybrid or Electric aircraft	2018	IATA	Aircraft Technology Roadmap to 2050
Hybrid or Electric aircraft	2017	NASA	Overview of NASA Electrified Aircraft Propulsion Research for Large Subsonic Transports
Hybrid or Electric aircraft	2018	F. Fusalba / J. Oriol	L'électrification des aéronefs – Techniques de l'ingénieur
Hybrid or Electric aircraft	2014	Mark H. Shushnar	Battery aircraft feasibility investigation including A B
Hybrid or Electric aircraft	-	EVIATION	Eviation Alice website
Hybrid or Electric aircraft	2019	ICAO	Electric, Hybrid, and Hydrogen Aircraft – State of Play
Hybrid or Electric aircraft	2018	Green Future AS / Jan Otto Reimers	Introduction of ekectric aviation in Norway
Hybrid or Electric aircraft	2016	NASA / J. L. Felder et al	NASA Electric Propulsion System Studies
Hybrid or Electric aircraft	2020	MAHEPA project	Mahepa project website
Hybrid or Electric aircraft	2019	You tube video	15 aéronefs en développement. Avion personal VTOL (https://www.youtube.com/watch?v=0WZZz8I8yMc)
Hybrid or Electric aircraft	2019	Y. Zhang	Performance and ageing quantification of electrochemical energy storage elements for aeronautical usage
Hybrid or Electric aircraft	2020	OXYS ENERGY / M. Crittenden	With Ultralight Lithium-Sulfur Batteries, Electric Airplanes Could Finally Take Off

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Item	Year	Author or ENTITY	Title
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Battery technologies	2017	CEA / F. Perdu	Overview of existing and innovative batteries
Battery technologies	2017	T. PLACKE and al.	Lithium ion, lithium metal, and alternative rechargeable battery technologies: the odyssey for high energy density
Battery technologies	2019	VITO	Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1 TASK 4
Battery technologies	2018	M. Meeus	Overview of Battery Cell Technologies
Battery technologies	2020	Sauvant-Moynot et al	État de l'art et perspectives des batteries de voitures électriques
Battery technologies	2013	J.M. Tarascon et al.	Enjeux et défis du stockage électrochimique de l'énergie
Battery technologies	2015	SAMSUNG SDI	Introduction of Samsung SDI's 94Ah cells
Battery technologies	-	Battery University	Battery University website
Battery technologies	-	SAFT	SAFT website
Solid battery	2019	O. Hajndl	Batterie tout solide pour application automobile : processus de mise en forme et étude des interfaces
Li-metal battery	-	SION Power	SION Power website
Li-S battery	2019	INERIS	Batteries haute densité énergétique au Li-S: différences avec la technologie Li-ion, évaluation des risques et mise en sécurité
Li-S battery	-	OXYS Energy	OXYS Energy website
Lithium-air battery	2014	K. G. Gallagher et al	Quantifying the promise of lithium–air batteries for electric vehicles
Supercap and LiC	2017	M. Keenan	Hybrid capacitors combine technologies to get the best of both worlds
LiC	-	JM Energy	JMenergy website

4 Energy storage

Bibliography 3/4:

Item	Year	Author or ENTITY	Title
Battery safety	2019	CEA / N. Guillet	Les risques liés aux batteries Li-ion
Battery safety	2014	JTSB	Aircraft serious incident investigation report
Battery safety	2016	NASA / Walker W. Q.	Short course on lithium ion batteries
Battery safety	2018	BMW / S. Scharner	Quantitative safety characterization of li-ion cells
Battery safety	2018	Xiang Liu and al.	Thermal runaway of lithium-ion batteries without internal short circuit
Battery safety	2018	Xuning Feng and al.	Key characteristics for themral runaway of Li-ion batteries
Battery safety	2018	T. Bartsch and al.	Gas evolution in all-solid-state battery cells
Direct cooling	-	3M	3M website
Battery cooling	2020	CEA / F. Pra	Everlasting D8.14 – White Paper 11
Battery integration	2018	M. Padgett	Audi details battery for 2019 e-tron electric
Structural battery	2018	W. Johannisson and al.	Multifunctional performance of a carbon fiber UD lamina electrode for structural batteries
Structural battery	2018	Giulia Fredi et al 2018	Graphitic microstructure and performance of carbon fibre Li-ion structural battery electrodes
Structural battery	2018	A. E. Scholz	Feasibility analysis and comparative assessment of structural power technology in all-electric composite aircraft
Structural battery	2018	A Javaid and M Zeshan Ali	Multifunctional structural lithium ion batteries for electrical energy storage applications
Structural battery	2019	W Johannisson et al 2019	Model of a structural battery and its potential for system level mass savings
Materials and process	2015	G Teyssedre, L BOUDOU	Polymer and composite for electrotechnique
Materials and process	-	Sorcerer	Structural Power Composites
Materials and process	2020	J. Sloan	Clean Sky project targets multifunctional composites for electric aircraft
Materials and process	2020	Alexandre Couto	[Dossier Impression 3D] La chasse aux kilos s'intensifie dans l'aérospatial
Materials and process	2019	M Thomas et al	Fabrication additive en aéronautique et en spatial
Materials and process	-	EOS	Part for aircraft from the 3D printer Produce efficiency and sustainably with additive manufacturing

4 Energy storage

Bibliography 4/4:

Item	Year	Author or ENTITY	Title
Energy storage	2019	S. Koohi-Fayegh and al.	A review of energy storage types, applications and recent developments_Koohi-Fayegh_2020
Energy storage	2016	R. Amirante and al.	Overview on recent developments in energy storage Mechanical, electrochemical and hydrogen technologies_Amirante_2017_Ragone
Fuel cell and H2 roadmap	2019	FCH2 JU report	Hydrogen roadmap Europe
Fuel cell and H2 roadmap	2020	Le Monde (French newspaper)	Airbus ambitionne de commercialiser un avion à hydrogène en 2035
Fuel cell and H2 roadmap	2018	B. James	2018 cost projections of PEM Fuel Cell Systems for Automobiles and Medium-duty Vehicles
H2 roadmap	2017	UsDrive	Hydrogen Storage Tech Team Roadmap
H2 roadmap	2015	IEA	Technology roadmap Hydrogen and Fuel Cells
H2 roadmap	2019	C. Houchins and al.	2019 DOE Hydrogen and Fuel Cells Program Review - H2 cost analysis
H2 roadmap	2020	CleanSky2 JU and FCH2 JU	Hydrogen-powered aviation. A fact based study of H2 technology, economy and climate impact by 2050

5.1.2 Full-electric propulsion system

A fully electric system relies upon a battery or some other means of electrical energy source as a sole means to power the propulsion system.

+ no emission

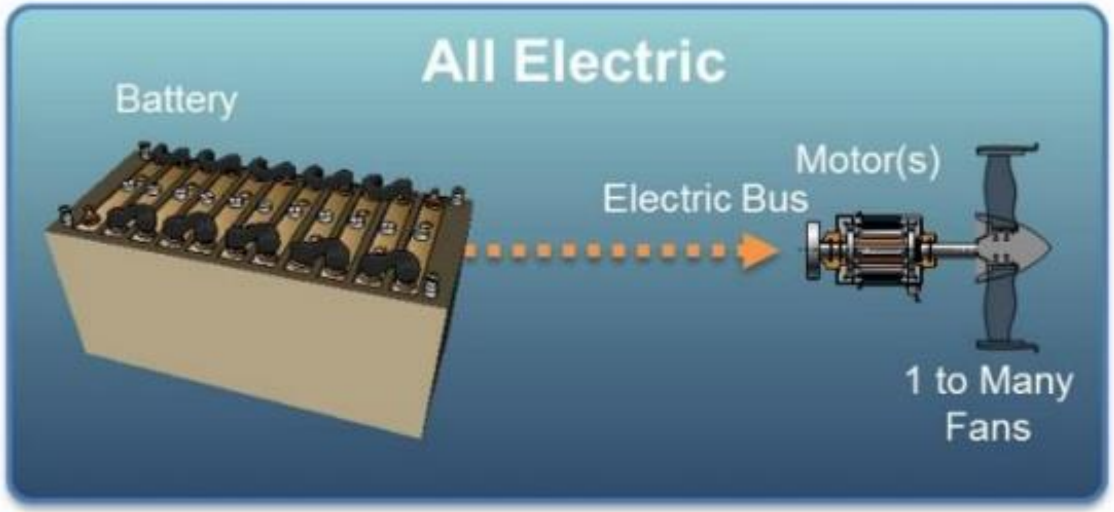
+ low cost of flight

- high weight because of batteries

- low range

Full electric propulsion system consisit on:

- Electic motors
- Energy storage system (battery, fuel cells)
- Power managment system



Source:

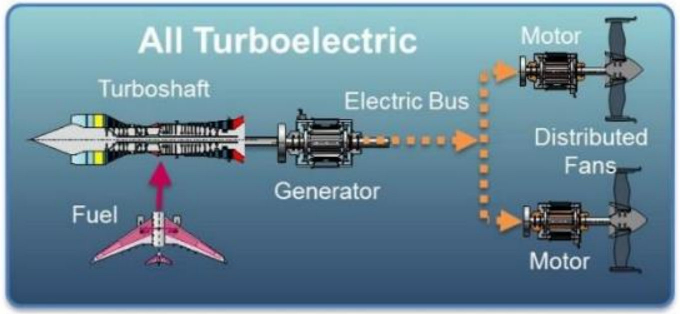
- Turbo- and Hybrid-Electrified Aircraft Propulsion Concepts for Commercial Transport, NASA, 2018

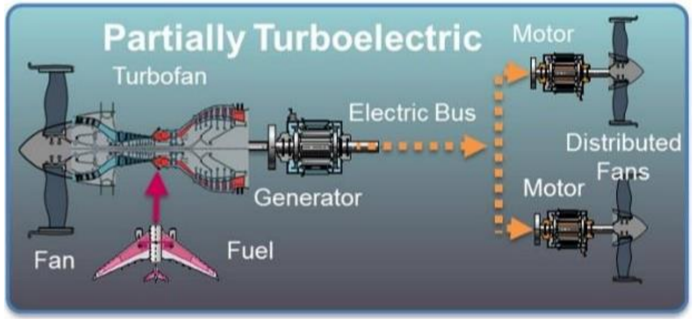
5.1.2 Full-electric propulsion system

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	**[4-6]** ✓	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	**35% < P < 65%** ✓	> 65%	High weight of batteries
Design tools Maturity TODAY	In house academy	**General Available** ✓	Commercial	
A/C level impact : integration synergy potential			✓	Power feed to electric systems
Regulatory Status Readiness / Maturity			✓	
Maturity for circular economy / Life Cycle @ EIS			✓	
Potential for diminishing emissions	Low / Indirect	Direct	**High** ✓	Zero-emisson of COx and NOx
Operations impact	**No change** ✓	Medium	Paradigm Shift	
Complexity	**No change / Minor Increase** ✓	Medium Increase	High Increase	Why? What parts?

5.1.3 Turbo-electric propulsion system

Turboelectric configuration retains fuel as main source of energy and converts the chemical energy available in the fuel into electrical power either fully or partially to drive the propulsor. Such configuration features lower efficiency due to the additional losses in the electrical drive system for the conversion and transmission of mechanical power to electrical power and again from electrical to propulsive power. However, on the positive side, the concepts are well poised for implementing the novel concepts such as distributed propulsion arrangement with or without a boundary layer ingesting system.





Turbo-electric propulsion system consisit on:

- Electic motors
- Power managment system
- Generator
- Converter
- Gas Turbine Engine

Source:

- Hybrid-Electric and Distributed Propulsion Technologies for Large Commercial Air Transports: A NASA Perspective, 2016
- Turbo- and Hybrid-Electrified Aircraft Propulsion Concepts for Commercial Transport, NASA, 2018

5.1.3 Turbo-electric propulsion system

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	[1-3]	**[4-6]** ✓	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%** ✓	Components of system have necessary perfomance
Design tools Maturity TODAY	In house academy	**General Available** ✓	Commercial	
A/C level impact : integration synergy potential			✓	Power feed to electric systems
Regulatory Status Readiness / Maturity			✓	
Maturity for circular economy / Life Cycle @ EIS		✓		
Potential for diminishing emissions	Low / Indirect	**Direct** ✓	High	NOx, COx
Operations impact	**No change** ✓	Medium	Paradigm Shift	
Complexity	**No change / Minor Increase** ✓	Medium Increase	High Increase	Why? What parts?

5.1.4.1 Hybrid series propulsion system

In a serial hybrid configuration, the propulsors are supplied electrically either from a gas turbine driven generator or from an electrical energy source. This arrangement enables decoupling of the gas turbine system from the propulsors by an electrical conversion and the transmission system. The inherent advantage of serial hybrid electric configuration is the flexibility to operate the gas turbine independent of the fan speed, thus making it feasible to operate at its maximum efficiency.

+low emission

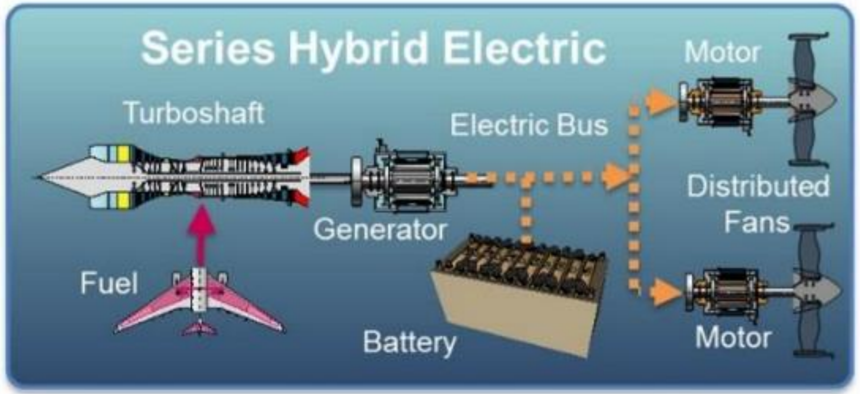
+low fuel consumption

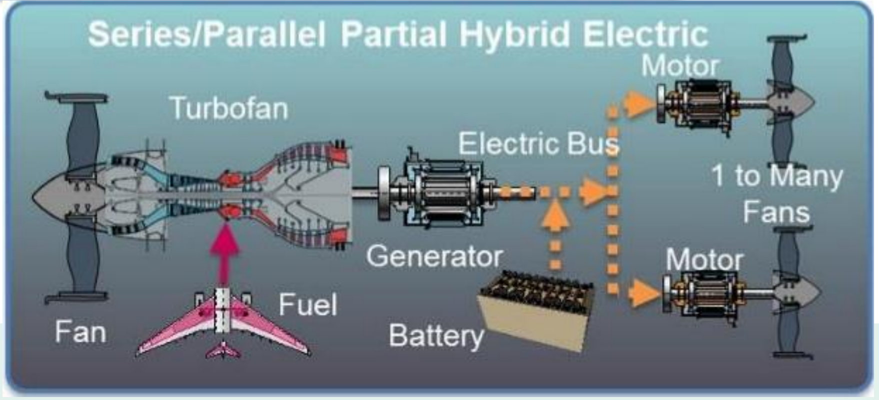
-heavy weight of system

-low fault-tolerance because of one engine

Hybrid series propulsion system consisit on:

- **-Electic motors**
- **-Energy storage system**
- **-Power managment system**
- **-Generator**
- **-Converter**
- **-Gas Turbine Engine**





Source:

- **Architecture, Voltage, and Components for a Turboelectric Distributed Propulsion Electric Grid, NASA report, 2015**
- **Turbo- and Hybrid-Electrified Aircraft Propulsion Concepts for Commercial Transport, NASA, 2018**

5.1.4.1 Hybrid series propulsion system

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	[1-3]	**[4-6]** ✓	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%** ✓	Components of system have necessary perfomance
Design tools Maturity TODAY	In house academy	**General Available** ✓	Commercial	
A/C level impact : integration synergy potential			✓	Power feed to electric systems
Regulatory Status Readiness / Maturity			✓	
Maturity for circular economy / Life Cycle @ EIS	✓			
Potential for diminishing emissions	**Low / Indirect** ✓	Direct	High	NOx, COx in airport zone
Operations impact	**No change** ✓	Medium	Paradigm Shift	
Complexity	No change / Minor Increase	**Medium Increase** ✓	High Increase	Additional electric motors

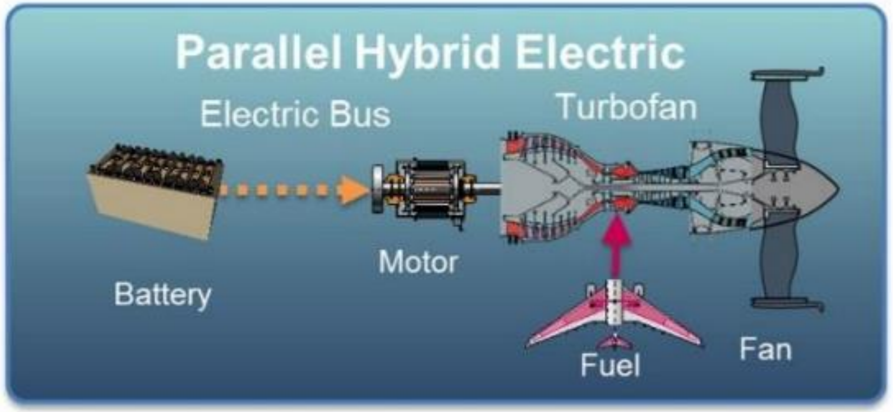
5.1.4.2 Hybrid parallel propulsion system

In Parallel hybrid propulsion system, both the electrical system and gas turbine system are connected mechanically to drive the propulsors, either in conjunction or in-lieu. In this arrangement, the electrical motor is mounted on the low-spool shaft of the engine and backed up with an electrical energy source that can either be charged onboard or on the ground. With a benefit of requiring less numbers of components, the configuration enjoys advantages related to weight saving. Nonetheless, on the downside, it involves mechanical coupling which causes operational and control complexity.

+high fault-tolerance

-higher emission than series

-higher fuel consumption than series



Hybrid series propulsion system consist on:

- Electic engines
- Energy storage system
- Power managment system
- Gas Turbine Engine

Source:

- Hybrid-Electric and Distributed Propulsion Technologies for Large Commercial Air Transports: A NASA Perspective, 2016
- Turbo- and Hybrid-Electrified Aircraft Propulsion Concepts for Commercial Transport, NASA, 2018

5.1.4.2 Hybrid parallel propulsion system

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	[1-3]	**[4-6]** ✓	>7	Evidence?
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	**> 65%** ✓	Components of system have necessary perfomance
Design tools Maturity TODAY	In house academy	**General Available** ✓	Commercial	
A/C level impact : integration synergy potential			✓	Power feed to electric systems
Regulatory Status Readiness / Maturity			✓	
Maturity for circular economy / Life Cycle @ EIS		✓		
Potential for diminishing emissions	Low / Indirect	**Direct** ✓	High	NOx, COx
Operations impact	**No change** ✓	Medium	Paradigm Shift	
Complexity	No change / Minor Increase	**Medium Increase** ✓	High Increase	Additional electric motors and batteries

5.2 Advanced Gas Turbine Engines

Aneto high power engine family is designed for new super-medium and heavy helicopter market. It will feature several models covering 2,500 to over 3,000 shp power range.

Aneto engine family bring significant benefits, which especially useful in demanding roles such as offshore transport, search and rescue, fire-fighting, law enforcement or military transport, as well as better performance in "hot and high" conditions.

Designed for next generation rotorcraft, Aneto is also a perfect drop-in engine solution for existing model.

Specifications:

P=2,500 ÷ 3,000+ shp

Fiatures :

- 15 % better fuel economy
- 25% power-to-valume ratio improvement
- Better performance in "hot and high" conditions
- Reduced environmental footprint

ANETO turboshaft engine (***Safran Helicopter Engines***)

?https://www.safran-helicopter-engines.com/aneto-1k-0

5.2 Advanced Gas Turbine Engines

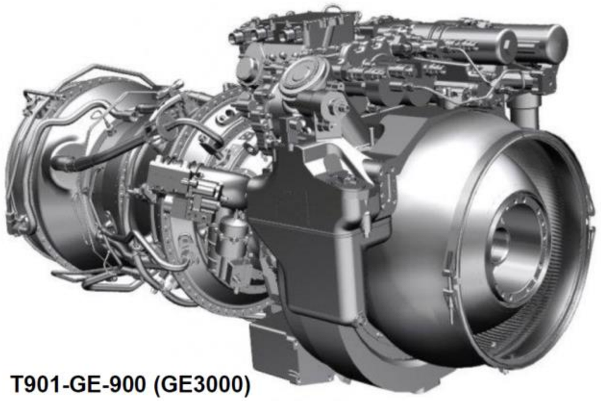
The T901-GE-900 & T900 turboshaft engines were developed under the Improved Turbine Engine Program with use of advanced technologies:

- **CMC in hot section of engine**
- **Additive manufacturing for some engine components**
- **Advanced cooling technologies**
- **Sand-tolerant technologies**

Specifications:
P=1,500 ÷ 3,000 shp
Fiatures:

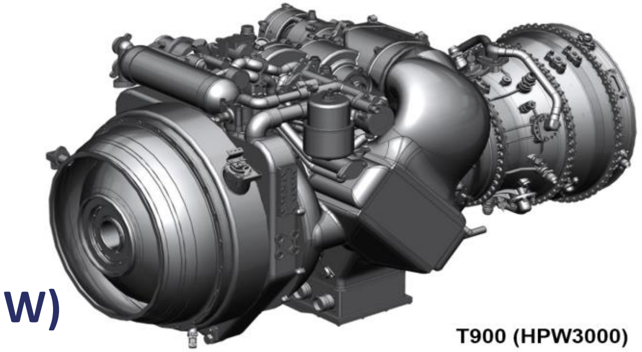
- **25% improved specific fuel comsumpsion**
- **50% better power**
- **25% longer design life**
- **Low maintenance operation**

GE Aviation



T901-GE-900 (GE3000)

ATEC (PW+HW)



T900 (HPW3000)

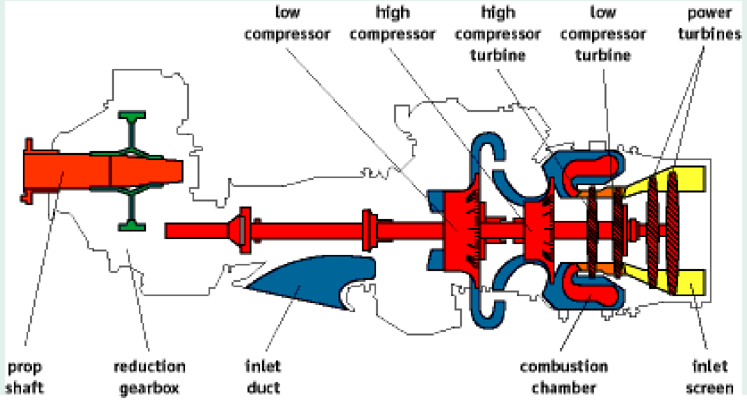
https://www.geaviation.com/military/engines/t901-turboshaft-engine

https://www.atecadvantage.com/

5.3 Gas turbine engine (turboprop core)

Reliant on basic Joule cycle. 2 shaft gas generator with centrifugal compression to reduce size and weight; power output is converted into thrust via a geared propeller. Relatively low TET to favour durability and low maintenance cost. Evolutionary trend to increase power to allow shorter TOFL and operation at higher temperature, rather than performance improvement. Market dominated by P&WC 100 and 150 series.

Reliable and well-known application at design and off-design; low cost and high power density, possibility of cycle improvement; easily scalable and flexible. Limited margin of components' improvement; relatively low thermal efficiency



Technical data current [future projections]:

Thermal efficiency: 32% [37%] (ESFC of 80 [65] ug/J circa)

Peak temperature: 1300 [1400] K

Overall ressure ratio: 14-18 [18-20]

Power to weight ratio: 3.8 [4.5] kW/kg, increasing with size

Specific power: 270 [300] kW/kg/s

Rotational speed: 30 krpm for core, 1200 power shaft.

Synergy/integration

Easy integration with elctric technologies and distribution propulsion. Would benefit from combination of fuel cell and/or topping cycle as long as size is not significantly affected.

D'Angelo, M.M, Gallman J., Johnson, V., Garcia E., Tai J., Young R., N+3 Small Commercial Efficient and Quiet Transportation for Year 2030-2035, NASA NASA/CR–2010-216691

Walsh, Fletcher, Gas turbine performane, 2nd ed., Blackwell Publishing 2008

https://engineering.purdue.edu/~propulsi/propulsion/jets/tprops/pw100.html

5.3 Gas turbine engine (turboprop core)

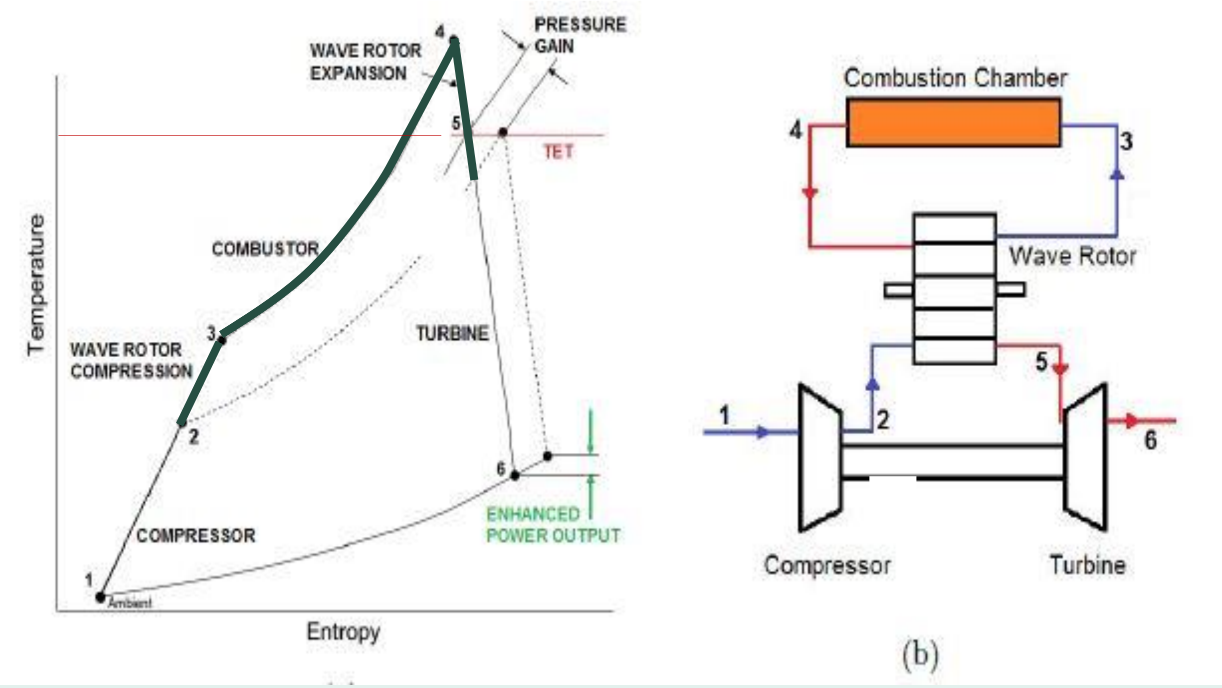
Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY			9	In service
Probability of Technology Readiness Level 6/7 in 2030			100%	In service
Design tools Maturity			Commercial	-
A/C level impact : integration synergy potential			X	Power feed to electric systems
Regulatory Status Readiness / Maturity			X	-
Consortium experience today			X	
Life cycle			X	-
Maturity for circular economy (eg, recycle? re-use)		Unknown		
Potential for diminishing emissions		Nox, Noise		Novel combustion techniques
		CO2		increas of efficeincy
Operations impact		No change		
Complexity	No change			
Price Point	No change			

5.4.1 Wave Rotor topping cycle

WR is a set of cylindric channels where compression/expansion happen via shock waves. Hot and clod two fluids are in direct contact, limiting cooling requirement. Suitable for small pressures and mass flows, as it is not penalised by blade height.

As a topping cycle allows higher OPR and COT, as TET is met from initial expansion. Efficiency is inversely proportional to the shock wave. It can be combined with external or internal combustion. Off design performance similar to gas turbines.

The device is small and light (low cost); higher TRL compared to other novel cycles. Requires complex ducting; high fraction of combusted gases trapped limits effective volume available



Technical data

Thermal efficiency: 36%

Peak temperature: 1800 K

Overall pressure ratio: 24 (device PR = 1.6-2)

Power to weight ratio: 4.3

Specific power: 300 kW/kg/s

Rotational speed: 30 krpm for core, 1200 power shaft.

P. Akbari, R. Nalim, N. Mueller, A Review of Wave Rotor Technology and Its Applications, J. Eng. Gas Turbines Power. Oct 2006, 128(4): 717-735 https://doi.org/10.1115/1.2204628

https://www.grc.nasa.gov/WWW/cdtb/projects/waverotor/

L. Gallo, Design Space Exploration of Distributed Propulsion HALE UAVs Burning Liquid Hydrogen, PhD thesis, Cranfield University, 2015

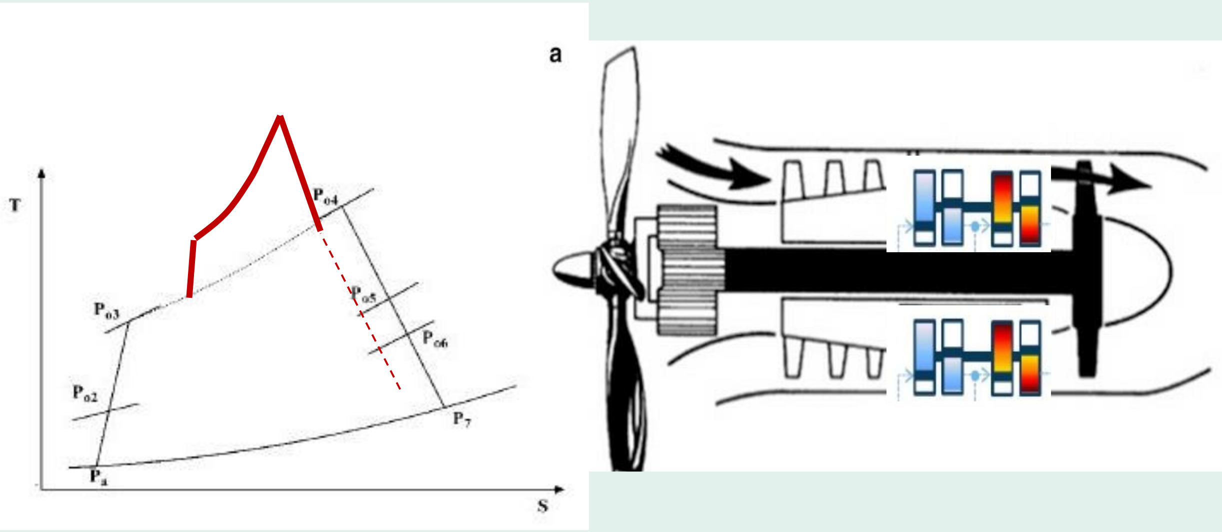
5.4.1 Wave Rotor topping cycle

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY		4		Experimental tests for standalone WR.
Probability of Technology Readiness Level 6/7 in 2030		60%		Used in automotove application
Design tools Maturity		General Available	Commercial	
A/C level impact : integration synergy potential		X		-
Regulatory Status Readiness / Maturity		X		Supposed same as conventional engine
Consortium experience today	X			
Life cycle			X	
Maturity for circular economy (eg, recycle? re-use)			X	Simple device
Potential for diminishing emissions		CO2, NOX, noise		
Operations impact	No change			Novel combustion techniques
Complexity		Medium increase		
Price Point	Minor increase			

5.4.2 Otto compound cycle

Piston engine are used in light aircraft. It is based on the motion of a reciprocating piston which powers a crankshaft. Constant volume combustion and very high cycle peak temperature allow higher efficiency compared to gas turbines. Ina combined cycle, a piston engine can replace (or work in parallel to) HP shaft and combustion chamber, to yield higher efficiency.

Piston engines and gas turbine are well-known and reliable, lowering development cost. Weight of the piston engine makes is more suitable for large units. A SFC reduction of 10% circa can be obtained. The combined cycle engine is anyway heavy and difficult to integrate.



Technical data:

Thermal efficiency: 42%

Peak temperature: 2100 K

Overall pressure ratio: 45 (device PR = 12 vor vPR=7)

Power to weight ratio: 1.9

Specific power: 300 kW/kg/s

Rotational speed: <5000 rpm

Synergies:

Large power offtake possible for electric motors and system.

Eilts P., Friedrichs J., “Investigation of a Diesel Engine for Aircraft Application”, AIAA Propulsion and Energy Forum, Atlanta, GA, USA, July 2017. DOI: 10.2514/6.2017-4792

Kaiser S., et al., “Composite Cycle Engine Concept with Hectopressure Ratio”, Journal of Propulsion and Power, 32(6), 2016. DOI: 10.2514/1.B35976

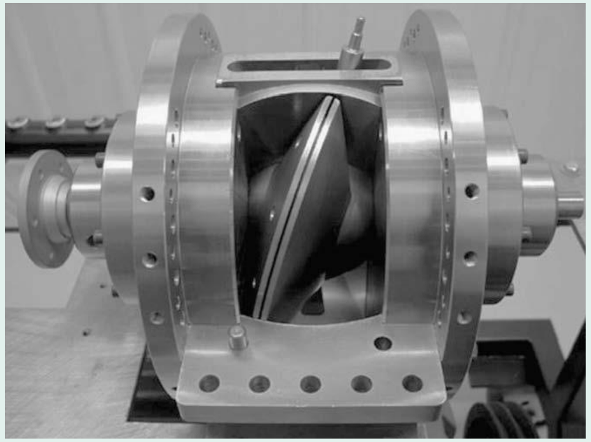
5.4.2 Otto compound cycle

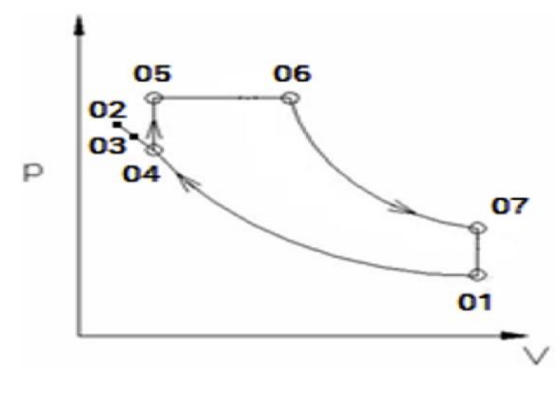
Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	3			For combined cycle
Probability of Technology Readiness Level 6/7 in 2030		40%		Easier development path
Design tools Maturity			Commercial	
A/C level impact : integration synergy potential		X		
Regulatory Status Readiness / Maturity			X	
Consortium experience today		X		
Life cycle		Unknown		
Maturity for circular economy (eg, recycle? re-use)		X		Same as current engine
Potential for diminishing emissions	Noise, NOx	CO2		
Operations impact	No change			
Complexity			High increase	Depending on configuration
Price Point		Medium increase		

5.4.3 Nutating Disc

The nutating disc is a compact device based on nutation of a disc around a Z-shaft. One side provides compression, the other expansion. First developed for drones and UAV, is competitive with gas turbines under 500kW for its small volume. Its cycle can flexibility include constant pressured and constant volume combustion. Opening valves can be positioned to tune volume of the chambers.

It can be used instead to replace HP shaft and combustion chamber. It has smooth torque transmission and can each high pressure ratio. It is penalised by the complexity , as several units need to be stacked to reach MW-range power. There are no detailed studies on off-design performance for general aviation.





Technical data

Thermal efficiency: 40%

Peak temperature: 1800 K

Overall pressure ratio: 40 (device PR = 10)

Power to weight ratio: 2.8

Specific power: 280 kW/kg/s

Compression/expansion efficiency: 90%

Ssynergies:

Motor for highly distributed configurations, or for secondary system.

Korakianitis T., et al., (2004). "Introduction and performance prediction of a nutating-disk engine". Journal of Engineering for Gas Turbines and Power. 126 (2): 294–99. doi:10.1115/1.1635394

Sebastiampillai J., et al., (2019). “Thermodynamic analysis of nutating disc engine topping cycles for aero-engine applications”, Energy 182 (2019): 641-655

5.4.3 Nutating Disc

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	2-3			Standalone technology tested in labs
Probability of Technology Readiness Level 6/7 in 2030	20%			
Design tools Maturity	In house academy			
A/C level impact : integration synergy potential	X			Possible use as APU (standalone)
Regulatory Status Readiness / Maturity	Low, few data available			
Consortium experience today	X			
Life cycle		Unknown		
Maturity for circular economy (eg, recycle? re-use)		Unknown		
Potential for diminishing emissions	NOx, Noise	CO2		
Operations impact	No change			
Complexity			High increase	
Price Point		Medium increase		

5.4.4 Pulse Detonation Combustion Engine

A PDC replaces existing deflagrative combustion chamber with tubes where detonation happens: the shock-induced compression, favoured by quick heat release, allows higher peaks of pressure and temperature than any other engine. The other components of engine remain unchanged.

The cycle has highest specific power, but high NOx production; unsteady flow is delivered to turbines. Equivalence ratio limited for NOx formation (lean combustion). Difficulty in deflagration to detonation transition. No detailed information available on off-design study.

Technical data:

Thermal efficiency: 38%

Peak temperature: 2000 K (2500 K if other fuels are used)

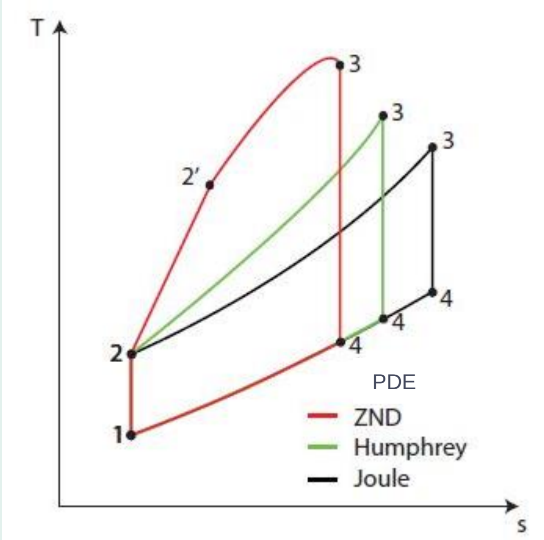
Overall pressure ratio: 24 (device PR = 1.6) – up to 80 bar can be reached

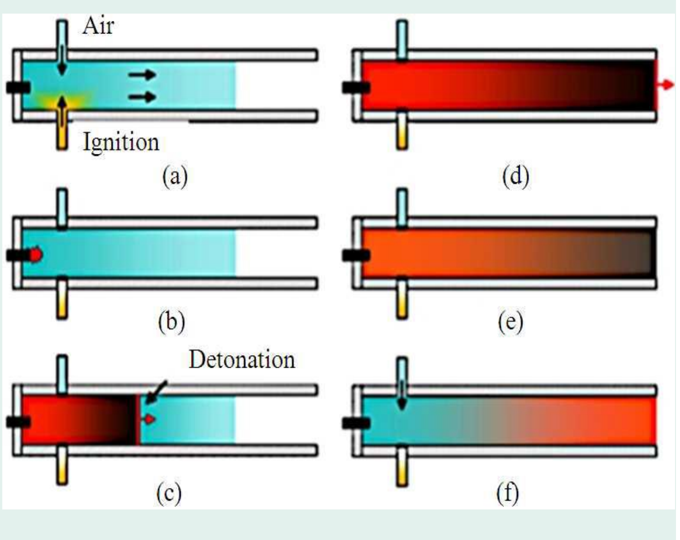
Power to weight ratio: 2.5

Specific power: 500 kW/kg/s

Equivalence ratio: 0.6-0.7 (to limit NOx)

Power to volume ratio: >10 MW/l (gas turbines circa 1)





Synergies:

Use fo hydrogen allows higher combustion temperatures. Higher specific power can act as enabler for smaller units

- Materano Blanco G., (2014). “Numerical Modelling of Pressure Rise Combustion for Reducing Emissions of Future Civil Aircraft”, PhD Thesis, Cranfield University

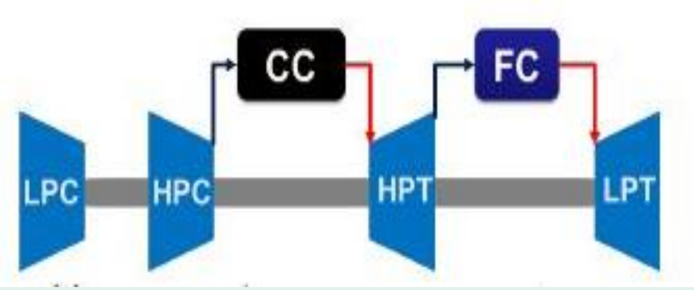
- Mawid M.A., et al., (2003). “Application of Pulse Detonation Combustion to Turbofan Engines”. *J. Eng. Gas Turbines Power*, Vol. 125, No 1, p.270–283

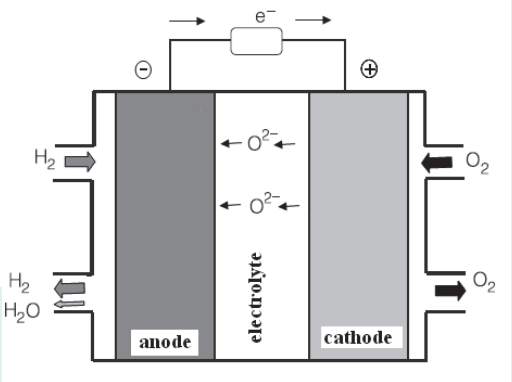
5.4.4 Pulse Detonation Combustion Engine

Quick Assessment Sheet	**Low**	**Medium**	**High**	**Comments**
Technology Readiness Level (TLR) TODAY	2			Preliminary study only.
Probability of Technology Readiness Level 6/7 in 2030	25%			
Design tools Maturity	In house academy			
A/C level impact : integration synergy potential	X			
Regulatory Status Readiness / Maturity	No or just working groups			Probably procedure for certification required
Consortium experience today	X			
Life cycle		X		
Maturity for circular economy (eg, recycle? re-use)			X	Tubes relatively simple
Potential for diminishing emissions	NOx, Noise	CO2		
Operations impact	No change			
Complexity		Medium increase		
Price Point		Medium increase		

5.4.5 Hybrid Solid Oxide Fuel Cell

Fuel cells convert directly fuel into electric power through chemical redox reaction. Placing between (or before) a turbine allows solid-oxide FCs to operate within good temperature range. Hybrid SOFC cycle highest efficiency and point emission reduction. Technology in consideration for industrial land-based application.





Technical data

Thermal efficiency: 60% (cycle)

Peak temperature: 1300 K

Overall pressure ratio: 15-18

Power to weight ratio: <1 kW/kg (cell only 0.1)

Specific power: 280 kW/kg/s

Cell voltage: 0.5-1 V

Cell volumetric density: 300 kW/m3

Synergies:

Direct electric production: efficient transfer to secondary system or power network. Use of different fuels (hydrogen)

Gallo, L., (2014). “Design Space Exploration of Distributed Propulsion HALE UAVs Burning Liquid Hydrogen”, PhD Thesis, Cranfield University, 2014

Roth, B. and R. Giffin (2010). “Fuel cell hybrid propulsion challenges and opportunities for commercial aviation”. In: 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference

5.4.5 Hybrid Solid Oxide Fuel Cell

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	2			Standalone FCs in operation
Probability of Technology Readiness Level 6/7 in 2030	10%			High technology gap before convenience
Design tools Maturity		General Available		-
A/C level impact : integration synergy potential		X		Electric systems, secondary power
Regulatory Status Readiness / Maturity	No or just working groups			Probably procedure for certification required
Consortium experience today		X		
Life cycle		Unknown		
Maturity for circular economy (eg, recycle? re-use)		Unknown		
Potential for diminishing emissions	Low/Indirect	Direct	CO2,NOx, Noise	Without considering aircraft level
Operations impact		Medium		Higher maintenance interval (?)
Complexity		Medium increase		
Price Point		Medium increase		

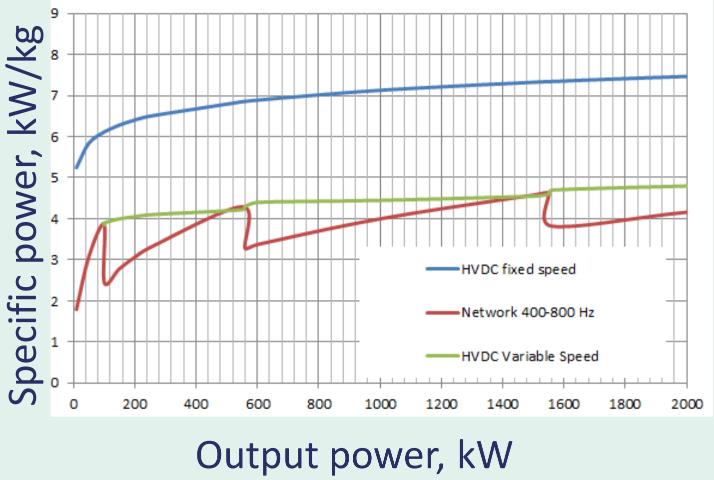
6.1 DC machines

Today high voltage DC system is very promising. The main idea is to produce energy by AC generators then transform it to DC and distribute. It gives opportunity to uncouple parameters of generator and loads and in turn decrease requirements for generator.

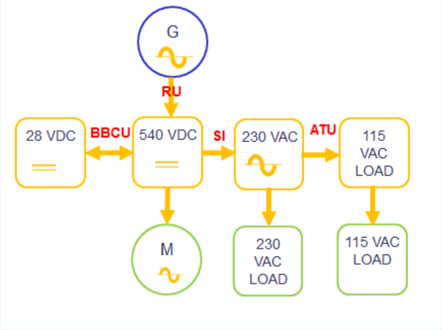
Advantages: possibility to increase speed of generators, possibility to parallelize generation units, simplification of the architecture, distribution network, the ability to directly supply power drives

In this case electrical generators and motors based on permanent magnets are very promising.

Difficulties: providing increased insulation strength because of HVDC bus using (increased risk of electric arcs and corona discharges); the need for switching devices for operating with large direct currents.



PROMISING ARCHITECTURE



For the 250 kW system:

1. In the case of using high-speed generators with constant speed and liquid cooling, their specific power can reach 6,5 kg.
2. Specific power of liquid-cooled power semiconductor converters reaches 4,5 - 5 kW / kg.

The total weight of the generator and converter is about 90 kg. Thus, the specific power of the channel generates about 2.7 kW / kg, which corresponds to this figure for the B787 generators. **BUT!** We have a direct current system, the total mass of which will be lower due to the centralized energy conversion and which has a number of other advantages.

1. Joël Devautour. Electrical Generation Trends & Prospective for Next Generation Aircraft. MEA 2019 Toulouse France 6-7 February 2019
2. K. Ni *et al.*, “Electrical and Electronic Technologies in More-Electric Aircraft: A Review,” *IEEE Access*, vol. 7, no. June, pp. 76145–76166, 2019, doi: 10.1109/ACCESS.2019.2921622.

6.1 Aviation generators

Conventional aviation generators are AC synchronous wound-field machines. In several cases DC contact machines are used (low power).

Most of aviation generators are 3 stage wound field machines. Their advantages are: autonomous, possibility for regulation, possibility of overload, reliability, possibility to realize starter regime, constant and variable output voltage. Disadvantages: complex construction, heavyweight.

Combination of advantages and disadvantages allow to use them as main generators for the biggest passenger aircraft B787.

It seems to be very difficult (maybe even impossible) to increase output power and specific power of such machines using existing architecture of electric system of airplane.

Example. B787 main generators:

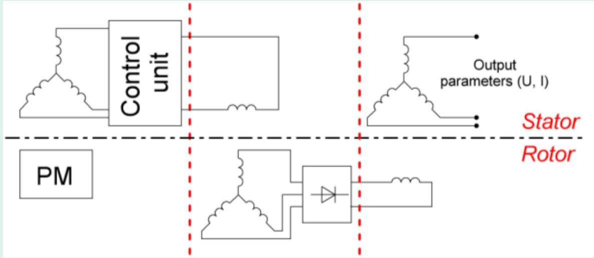
4 variable frequency SG, 250 kVA, oil cooled , independent oil;

Specific power:2,7 kW/kg

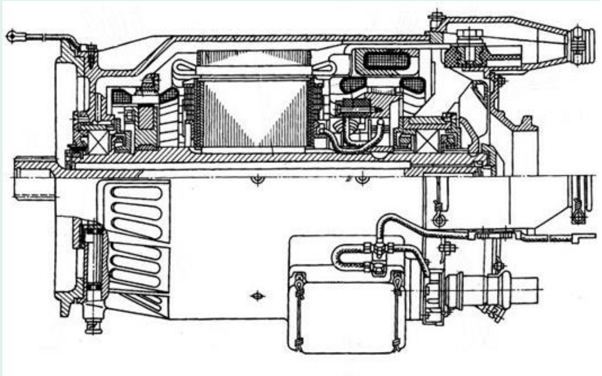
Rotation speed: 7200-16000 rpm

El. Frequency: 360-800 Hz

Most powerful generators are less than 3 kW/kg



Scheme of 3 stage machine



Construction of 3 stage machine

Thanks to possibility of regulation of output voltages this type of generators have advantages in the systems with wide range of loads. Besides this machine could be used to start engine.

1. Joël Devautour. Electrical Generation Trends & Prospective for Next Generation Aircraft. MEA 2019 Toulouse France 6-7 February 2019.
2. *AECS Gary Brown and AEC Leonard Bovender.* Aviation Electricity and Electronics—Power Generation and Distribution.
3. HyeonMyeong Woo, Dong-Hee Lee. Efficiency and Performance Analysis of a Generator - Exciter Combination System. 2019 International Conference on Clean Electrical Power (ICCEP). DOI: 10.1109/ICCEP.2019.8890118

6.1 Cryo magnets

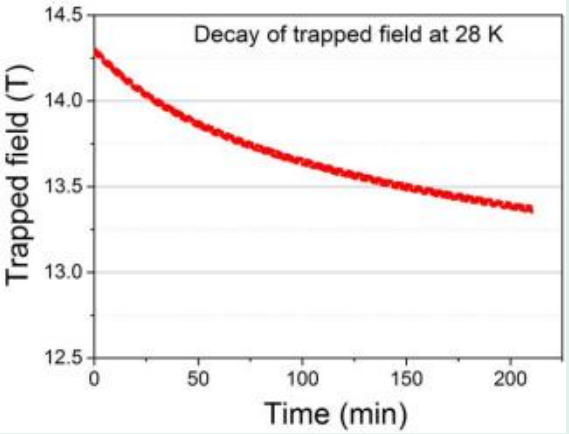
Bulk high-temperature superconductors (HTS) and stacks of high-temperature superconducting tapes with a trapped magnetic field are very promising technology. Bulk superconductors have the attractive property of being able to sustain persistent currents once magnetized, providing a highly compact source of stable magnetic field.

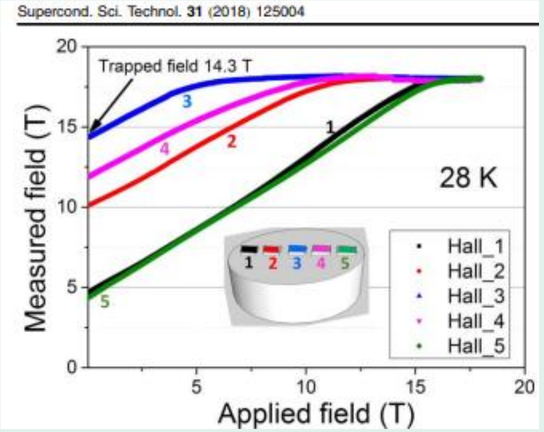
In general this technology is similar to permanent magnets: pulse magnetization of hard magnetic material. Differences are higher value of trapped field, cryogenic operating temperature, non-uniform value of trapped field and in time degradation.

HTS cryo magnets can be used as primary source of magnetic field in electrical machines. It will help to increase magnetic field density in the air gap and specific power of the machine. But it needs to take into account non-linear dependencies of HTS magnets properties.

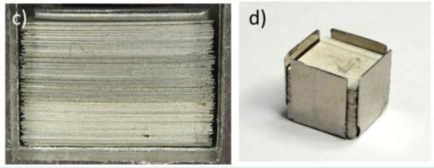
Maximum value of trapped field: 17.7 T at 10K.

Max temperature: 77 K




Supercond. Sci. Technol. 31 (2018) 125004

HTS bulk



Stack of HTS tapes

1. **A trapped field of 14.3T in Y–Ba–Cu–O bulk superconductors fabricated by bufferassisted seeded infiltration and growth.** Devendra K Namburi , John H Durrell , Jan Jaroszynski , Yunhua Shi , Mark Ainslie , Kaiyuan Huang , Anthony R Dennis , Eric E Hellstrom and David A Cardwell. Supercond. Sci. Technol. 31 (2018) 125004 (8pp). https://doi.org/10.1088/1361-6668/aae2cf

2. **A Trapped Field of 17.6 T in Melt-Processed, Bulk Gd-Ba-Cu-O Reinforced with Shrink-Fit Steel**. Durrell, J.H. , Dennis A. R. , Jaroszynski J. , Ainslie, M. D. , Palmer, K. G. B. , Shi Y-H , Campbell, A. M. , Hull, J. , Strasik, M. , Hellstrom, E., Cardwell, D. A.

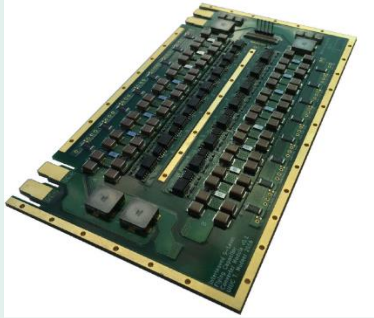
3. **Estimation of maximum possible trapped field in superconducting permanent magnets in 2D and 3D**. Víctor M. R. Zermeño , Algirdas Baskys , Shengnan Zou , Anup Patel. and Francesco Grilli.

4. **Trapped fields up to 2 T in a 12 mm square stack of commercial superconducting tape using pulsed field magnetization.** A Patel , S C Hopkins and B A Glowacki. doi:10.1088/0953-2048/26/3/032001

6.1 GaN transistors/Power Electronics

Among the possible semiconductor materials, which may replace the previous semiconductor, i.e. Silicon (Si) and Silicon Carbide (SiC), Gallium Nitride shows the best tradeoff including theoretical characteristics (high blocking voltage, capability, high-temperature operation, and high switching frequencies). Theoretical temperature range is up to 500° C, more than 200° C in laboratory conditions.

48V/12kW inverter with SiC (left) and GaN transistors (right)



10kW inverter module (100x200mm)

- Much lower gate driver losses (gate input capacitance is much lower than Si or SiC)
- Power inverters with GaN show higher performance even at higher frequencies.
- Switching power losses are almost temperature-invariant (50…100°C) compared to Si or SiC
- Suitable for cryogenic (100K and below) temperatures

- Possible structural integration with electrical or superconducting machines
- Cooling system integration with superconducting machines and cables

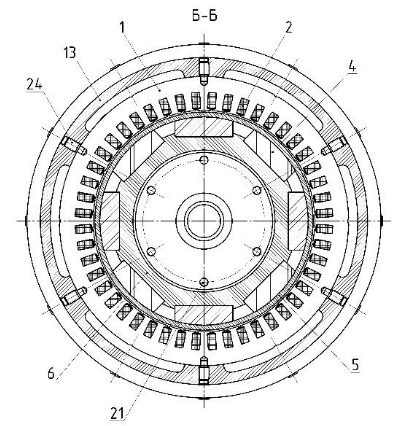
- https://gansystems.com/newsroom/egtronics-48v-12-kw-inverter/
- DOI 10.1109/TPEL.2015.2506400, IEEE Transactions on Power Electronics
- DOI: 10.1109/APEC.2018.8341239, 2018 IEEE Applied Power Electronics Conference

6.1.3 Permanent magnets machines

Machines with permanent magnets (PM) look very promising in aircraft application. It is connected with its simple construction, high energy of modern PM, mechanical properties of rotor and etc.

Machines with PM can be used as DC and AC motors. Due to high energy of PM these machines have high output power and thanks to recent advantages in power electronics they also have possibility for regulation.

Main disadvantage of machines with PM is absence of possibility of regulation. It is very important if machine operates as generator. Several techiques are known to provide regulation of machines with PM but it make construction more complex, increase weight. Besides value of regulation is limited by 30%



Autonomous.

High rotation speed – up to 60 000 rpm and more.

Max specific power for 2500 rpm – 5 kW/kg.

Possibility to operate as a motor/generator.

Special features needed to provide regulation.

Regulation is limited by 30%.

Short circuit danger.

Possibility to use as motor and generator.

Can be coupled with power converter to realise recuperation.

Very promising for systems with DC bus.

Direct connection with turbine can be used.

Dmitry Golovanov,Zeyuan Xu,David Gerada,Andrew Page andTadashi Sawata. Designing an Advanced Electrical Motor for Propulsion of Electric Aircraft. https://doi.org/10.2514/6.2019-4482

Ayman EL-Refaie, *Mohamed Osama.* High Specific Power Electrical Machines: A System Perspective. CES TRANSACTIONS ON ELECTRICAL MACHINES AND SYSTEMS, VOL. 3, NO. 1, MARCH 2019.

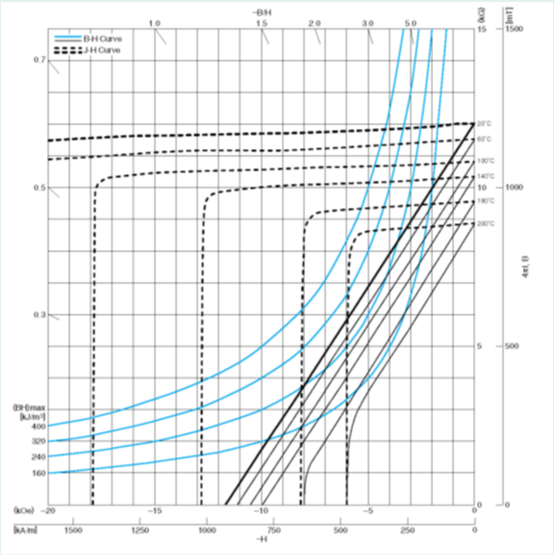
6.1.3 Permanent magnets

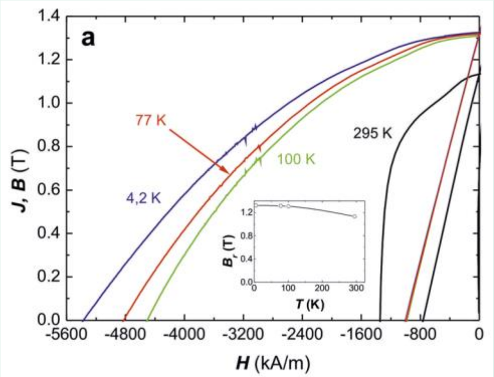
The most powerful permanent magnets are rare-earth magnets: neodymium (NdFeB) or samarium (SmCo).

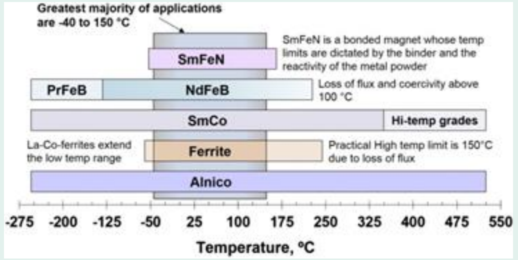
For electric machines application of PM is limited by operating temperature.

Today values of induction and coercitivity of reareath magnets are: Br=1.5, Hc=-1000kA/m. Parameters of PM decrase if temperature increase.

In praseodymium-doped magnets (NdPrFeB) operating temperature can be lower than the temperature of liquid nitrogen.







The most popular permanent magnets are NdFeB and SmCo.

The theoretical (BH) maximum value of the NdFeB magnet is 512kJ/m3 (64MGOe ~N64 mark),

N55 brand magnets are commercially available.

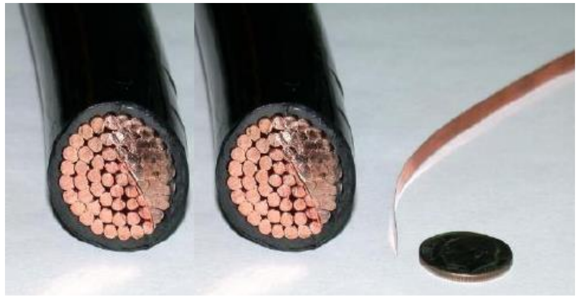
1. https://magneticsmag.com/permanent-magnets-in-a-changing-world-market/
2. https://magnet.com.au/faq/temperatures-that-permanent-magnets-operate.htmlhttps://www.magnet-sdm.com/sintered-neodymium-magnet/
3. **Nd2Fe14B and Pr2Fe14B magnets characterisation and modelling for cryogenic permanent magnet undulator applications.** C. Benabderrahmane n, P. Berteaud, M. Valle ´au, C. Kitegi, K. Tavakoli, N. Be ´chu, A. Mary, J.M. Filhol, M.E. Couprie
4. **(Pr, Ho)-Fe-B magnets for low-temperature applications**. Nataliya B. Kolchugina, Katerina Skotnicova , Aleksander A. Lukin, Gennadii S. Burkhanov, Ondrej Zivotsky , Miroslav Kursa, Nikolay A. Dormidontov, Pavel A. Prokofev, Yuri S. Koshkidko , Tomas Cegan, Tatiana P. Kaminskaya, and Boris A. Ginzburg. doi.org/10.1063/1.5129896@adv.2020.MMM2020.issue-1

6.1.6 Superconducting cables/Distribution Systems

Today the most interesting superconducting (SC) materials are high temperature superconductors (HTS).

Application of HTS cables is rational for high power low voltage systems. It is connected with high current carrying capacity of HTS cables. On the other hand HTS have non-linear magnetic, temperature and mechanical properties.

Important directions of R&D are attempts to reduce mass and dimensions of HTS cables for such applications as electrical aircrafts or ship propulsion systems. Such compact cables should have minimized diameter compared to other coaxial HTS cables developed before.



HTS-2G tape at 55K and copper equiv. @750A

HTS-2G compact multilayer cable, outer Dia 20mm, 3kA@77K, 20kV insulation

- High current-carrying density of HTS-2G tapes: from ≈0.5…1*10^3 at 77K to 1*10^4 at 4.2K
- Good mechanical properties of 2G HTS tapes: small bending radii, high mechanical strength.
- Versatile HTS-2G tapes usage: multilayer cable, CORC, stack of tapes, Roebel cable
- Numerical models for multilayer cables are already developed and approved by experimental results worldwide: Nexans, Kepco, JSC VNIIKP (Russia) and FSK EES (Russia).

- Possible structural integration superconducting machines
- Full system integration with superconducting machines (common cryostat)

- doi:10.1088/1757-899X/502/1/012179
- doi: 10.1109/TASC.2017.2652854
- doi:10.1088/0953-2048/25/1/014003
- DOI: 10.1109/TASC.2018.2821708

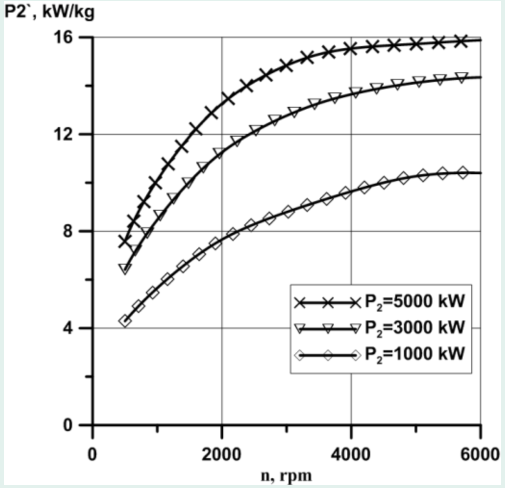
6.1.6 Superconducting machines

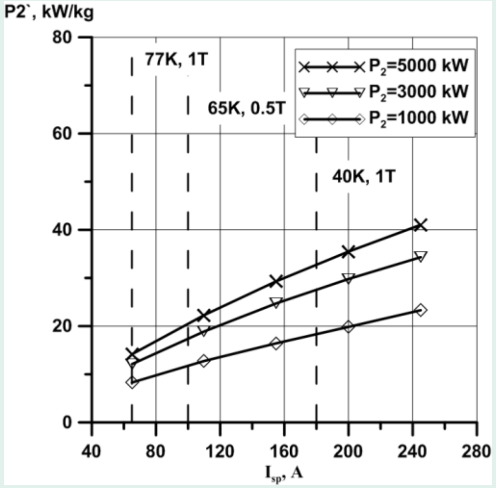
Today the most interesting superconducting (SC) materials are high temperature superconductors (HTS). They are thin tapes and bulks. Tapes could be used as windings of electrical machines. Both bulks and stacks of tapes could be magnetized and used as cryogenic magnets to produce magnetic field (like permanent magnets).

Application of HTS windings in electrical machines allows to decrease its weight and dimensions. Using HTS materials 20 kW/kg could be achieved.

Operating temperatures could be different but less than 77K (liquid nitrogen). Current capacity of HTS materials increases with temperature decreasing. The most promising is application of HTS windings operating at 20K (liquid hydrogen).

Parameters of HTS tapes has nonlinear dependency on temperature and external magnetic field. In this case design of HTS machines become more complex due to extra nonlinear dependencies.





- High current-carrying density of HTS-2G tapes: from ≈0.5…1*10^3 at 77K to 1*10^4 at 4.2K
- Good mechanical properties of 2G HTS tapes: small bending radii, high mechanical strength.
- Different types of machines and principal schemes could be used.
- Numerical models for several machine schemes are developed and approved by experimental results worldwide: University of Lorain (France), NASA (USA), KIT (Germany), MAI(Russia) and etc.

- Possible structural integration superconducting cables
- Full system integration with superconducting machines (common cryostat)
- Very promising technology for systems which use liquid hydrogen as a primary energy source.

DOI: 10.1109/TASC.2017.2787180

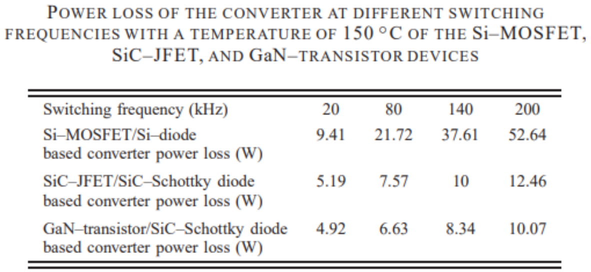
DOI: 10.1109/TASC.2009.2019021

DOI: 10.1088/1361-6668/aa833e

6.1.6 SiC transistors & diodes/Power Electronics

During recent years, silicon carbide (SiC) power electronics has gone from being a promising future technology to being a potent alternative to state-of-the-art silicon (Si) technology in high-efficiency, high-frequency, and high-temperature applications. The reasons for this are that SiC power electronics may have higher voltage ratings, lower voltage drops, higher maximum temperatures, and higher thermal conductivities. It is now a fact that several manufacturers are capable of developing and processing high-quality transistors at cost that permit introduction of new products in application areas where the benefits of the SiC technology can provide significant system advantages.

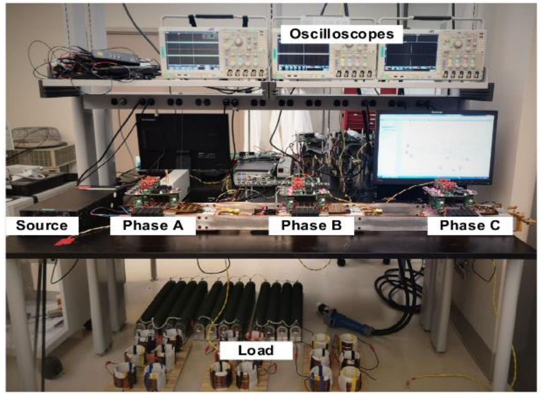
- SiC technology allows to rise up switching frequency of power devices up to 100...200kHz
- SiC devices with high blocking voltage (10kV) are avaliable on market, compared to approx. 6kV Si limit
- Specific on-resistance (mOhm*mm^2) tends to rise while tempreature gets below approx 120K
- Widely distributed on market since 2010s



POWER LOSS OF THE CONVERTER AT DIFFERENT SWITCHING FREQUENCIES WITH A TEMPERATURE OF 150 °C OF THE Si–MOSFET, SiC–JFET, AND GaN–TRANSISTOR DEVICES

Switching frequency (kHz)	20	80	140	200
Si–MOSFET/Si–diode based converter power loss (W)	9.41	21.72	37.61	52.64
SiC–JFET/SiC–Schottky diode based converter power loss (W)	5.19	7.57	10	12.46
GaN–transistor/SiC–Schottky diode based converter power loss (W)	4.92	6.63	8.34	10.07

MegaWatt-class inverter with cryocooling for aviation under test (Boeing/Nasa)



- Possible structural integration with electrical machines
- Limited cooling system integration with superconducting machines and cables

- **DOI:** 10.1109/NAPS.2017.8107192
- **DOI:** 10.1109/MIE.2012.2193291
- DOI: 10.1109/TPEL.2019.2952633
- DOI: 10.2514/6.2019-4473

6.1.6 Superconducting machines

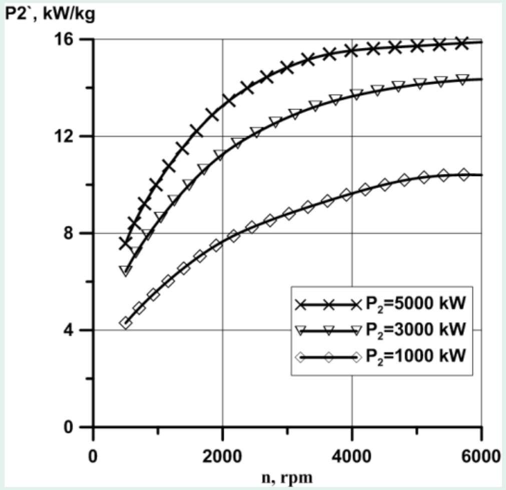
Today the most interesting superconducting (SC) materials are high temperature superconductors (HTS). They are thin tapes and bulks. Tapes could be used as windings of electrical machines. Both bulks and stacks of tapes could be magnetized and used as cryogenic magnets to produce magnetic field (like permanent magnets).

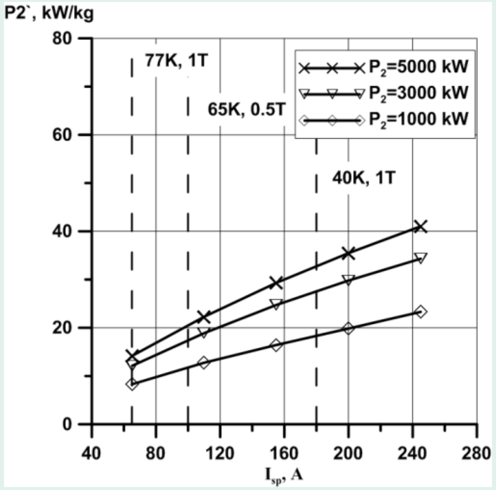
Application of HTS windings in electrical machines allows to decrease its weight and dimensions. Using HTS materials 20 kW/kg could be achieved.

Operating temperatures could be different but less than 77K (liquid nitrogen). Current capacity of HTS materials increases with temperature decreasing. The most promising is application of HTS windings operating at 20K (liquid hydrogen).

Parameters of HTS tapes has nonlinear dependency on temperature and external magnetic field. In this case design of HTS machines become more complex due to extra nonlinear dependencies.

- High current-carrying density of HTS-2G tapes: from ≈0.5…1*10^3 at 77K to 1*10^4 at 4.2K
- Good mechanical properties of 2G HTS tapes: small bending radii, high mechanical strength.
- Different types of machines and principal schemes could be used.
- Numerical models for several machine schemes are developed and approved by experimental results worldwide: University of Lorain (France), NASA (USA), KIT (Germany), MAI(Russia) and etc.





- Possible structural integration superconducting cables
- Full system integration with superconducting machines (common cryostat)
- Very promising technology for systems which use liquid hydrogen as a primary energy source.

DOI: 10.1109/TASC.2017.2787180

DOI: 10.1109/TASC.2009.2019021

DOI: 10.1088/1361-6668/aa833e

6.1 Soft magnetic materials for machines

Soft magnetic materials (SMM) are characterized with next parameters: B_s – magnetic induction of saturation, p_0 - specific losses, ρ - mass density.

For machines with high specific parameters it is necessary to increase the induction in magnetic cores up to 2.3 T. This is possible with application of cobalt magnetic alloys which has high saturation (Bs).

For high speed machines it is better to use steel with low losses such as 10JNEX900 (Japan) and 10JNHF600 (Japan).

Main parameters for different steels.

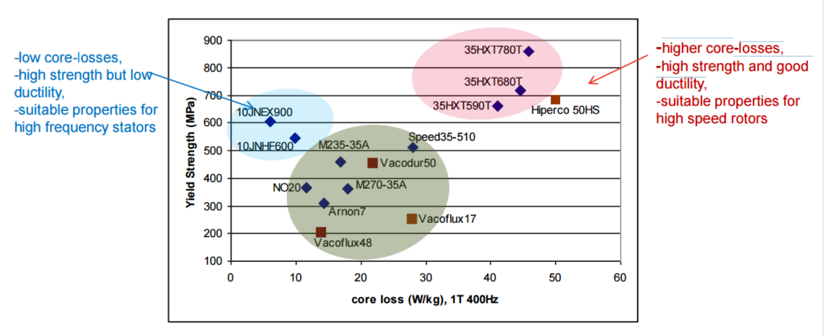
Structural ferromagnetic steels: Bs=1.7 , ρ =7800;

Electrical steel: Bs=1.8 , p_0= 20 W/kg (1T, 400 Hz), ρ =7850 kg/m^3

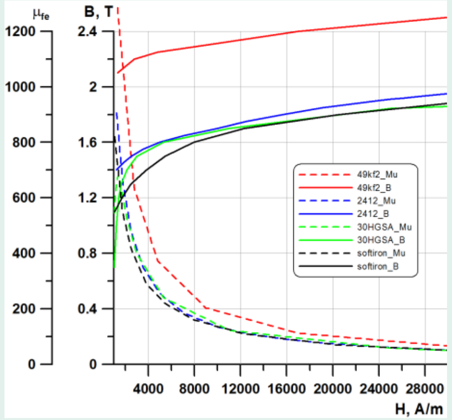
Steel with high saturation (VACOFLUX®, VACODUR®): B_s=2.3 T , p_0= 20 W/kg (1T, 400 Hz), ρ =8000 kg/m^3

Steel with low losses: B_s = 1.5 T, p_0= 7W/kg (1T, 400 Hz) , ρ =7500 kg/m^3.

The most perspective steels for electrical machines



Saturation curves and magnetic permeability for different steels.



1. Akira Chiba et. al. Torque Density and Efficiency Improvements of a Switched Reluctance Motor Without Rare-Earth Material for Hybrid Vehicles. IEEE Transactions on Industry Applications (Volume: 47 , Issue: 3 , May-June 2011)
2. https://docplayer.net/56849398-Soft-magnetic-cobalt-iron-alloys-vacoflux-and-vacodur.html
3. https://vacuumschmelze.com/Assets/Cobalt-Iron%20Alloys.pdf

European Commission

6.1 Composite materials for electrical machines

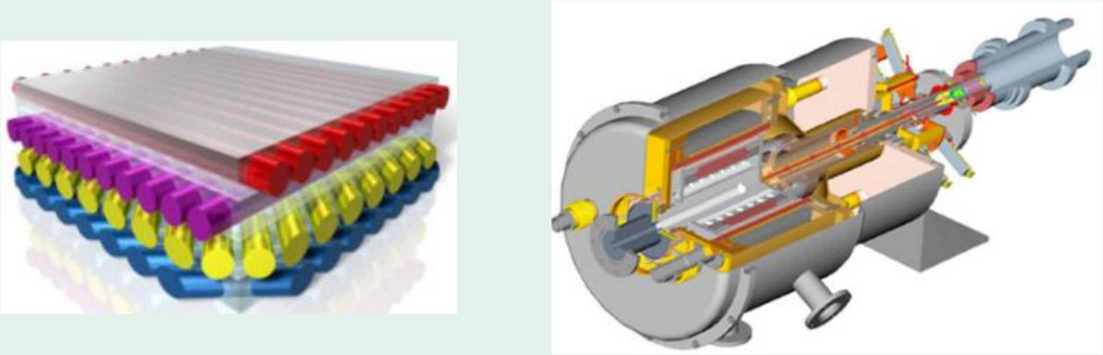
Brief Description

Products made of composite materials are widely used in the manufacture of electrical machines, due to their strength and stiffness characteristics, as well as corrosion resistance

Composite materials can be used for the manufacture of shafts, retainer shells of the rotor, stator teeth, bearing assemblies, etc.

The introduction of the technology will provide an increase in the specific characteristics of electrical machines and reduce the cost of maintenance.

Pictures



Technical Data

High specific strength (strength 3500 MPa)

High rigidity (elastic modulus 130 ... 140 - 240 GPa)

High wear resistance

High fatigue strength

Fabrication of dimensionally stable structures

Low specific gravity

Benefits/Synergies

- Improving the specific characteristics of electrical machines
- Reduction in repair costs and recovery

Drawbacks

- Immature

- References

Ismagilov F.R., Vavilov V.E., Sayakhov I.F. Diagnostics of composite materials in electrical machines

Kim K.K., Esin P.A., Ivanov S.N. Efficiency of application composite materials in electrical installations

Tong W., Wu S., Sun J., Zhu L. Iron Loss Analysis of Permanent Magnet Synchronous Motor with an Amorphous Stator Core. (2016). IEEE Vehicle Power and Propulsion Conference, VPPC 2016 – Proceedings 7791716

6.1 Composite materials for electrical machines

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] V	>7	Highly used in non-electrical techs
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65% V	> 65%	Lots of ucertanties
Design tools Maturity TODAY	In house academy	General Available V	Commercial	
A/C level impact : integration synergy potential			V	Any electrical system
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23 V	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	NA
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase V	High Increase	
Price Point	No change / Minor Increase	Medium Increase V	High Increase	Electrical composite

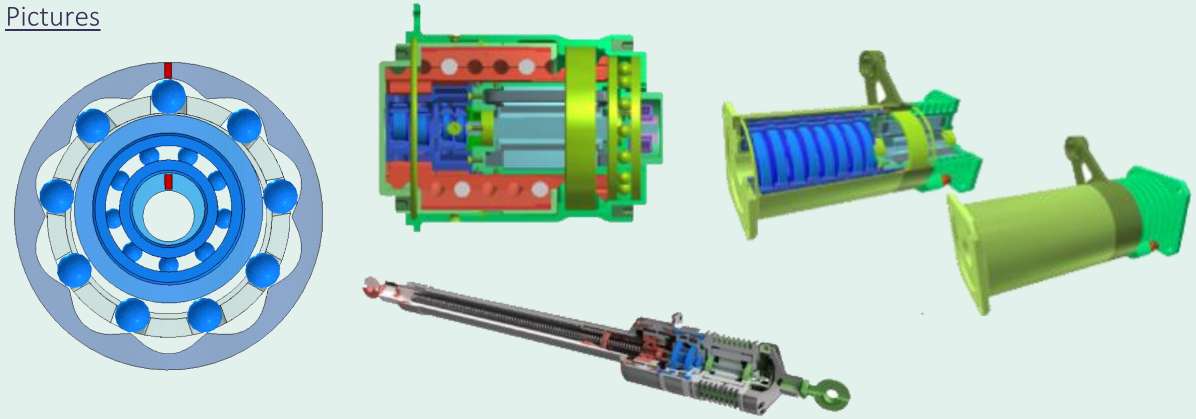
6.2 Electric drive with planetary- cycloid gearboxes

Brief Description

The main components of the Planetary- cycloid drive are a high-speed shaft with eccentrics, an internal flanged low-speed shaft, cycloidal disks and a gear housing. This gear has many contact points that provide simultaneous distribution of the work load to about half of all the teeth, so it can withstand an instant peak shock load, which is 5 times higher than the calculated torque.

Planetary- cycloid gearboxes can be effectively used in technical systems where it is required to provide high transmitted power with minimum dimensions and mass of the drive, high kinematic accuracy, reliability and durability.

Pictures



Technical Data

Brake cylinder

The pressing force is 28,000 N, the speed (20,000 N) is 40 mm / s,

Passband (Am = 1 mm) - 10 Hz, stroke - 15 mm

weight - 2.83 kg, Length - 110 mm, Diameter - 78 mm

Interceptor Drive

Weight - 7.7 kg, Length - 220 mm, Diameter - 91 mm

Maximum torque - 2,000 N H m

Maximum rotation speed - 70 deg / s

Benefits/Synergies

- High power density
- High specific volume
- Wide range of application
- low cost of installation and maintenance

Drawbacks

- Complexity
- High cost production

- References
- Base of patents of the Eurasian Union. Two-stage planetary gear reducer Author: Rudnovsky M.V. https://easpatents.com/6-16184-dvuhstupenchatyjj-planetarno-cevochnyjj-reduktor.html
- Production of prototypes and small series of electromechanical drives. Product Catalog http://nikosa.ru/catalog

6.2 Electric drive with planetary- cycloid gearboxes

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6]	>7 V	Used in many types of aircrafts
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% V	
Design tools Maturity TODAY	In house academy	General Available	Commercial V	
A/C level impact : integration synergy potential			V	Conrol system, actuator system
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23	Special Condition CS23 / CS 25 V	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	NA
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase V	High Increase	Gears
Price Point	No change / Minor Increase	Medium Increase	High Increase V	High accuracy, high quality of alloys

6.2 Valve-inductor motor

Brief Description

A valve-induction motor (VIM) is a stepper motor operating in constant rotation mode.

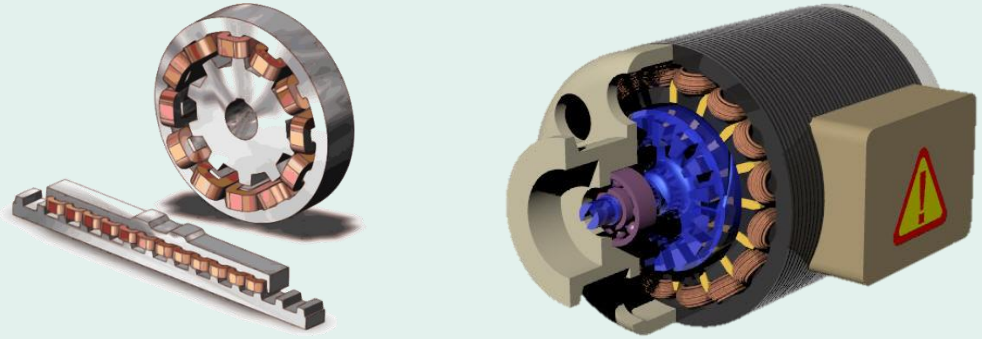
An adjustable electric drive based on the VIM makes it possible to control according to the characteristics of a specific load: adjust the speed, torque, power.

Simplicity of design, absence of moving contacts, no magnetic system, the absence of windings on the rotor, low price and high reliable electric machines of the VIM, are crucial for their application in aviation, as a managed failover of the power ensuring liveness properties.

It is necessary to use a control system that can be integrated into the VIM electric drive.

The engine VIM can switch to the mode of an inductor generator, which makes it possible to use the recovered energy.

Pictures



Technical Data

The price is 2 times lower compared to an asynchronous motor.

Increased specific power-to-volume ratio of steel-1.74 (for asynchronous motors-1.24).

Efficiency-86% (for asynchronous motors-81%).

Increased mechanical torque at low speeds and low currents.

Benefits/Synergies

- Development of highly reliable regulated fuel pumps with sufficient pressure.
- Managed drive the airflow of the ventilation system of the passenger cabin.
- Drive mechanisms for cleaning and releasing the chassis.

- References
- Electronic Control of Switched Reluctance Machines/Edited by T.J.E. Miller. Newnes, 2001, 272 p.
- Nesterov E.V. Determination of basic geometric parameters of a valve-inductor motor of a reversed design // Electricity. 2006 № 5 C. 63–65.
- Valve-inductor electric drive-application prospects / T.A. Ahtynov, L.N. Makarov, M.G. Buchkov, N.F. Ilinskii // Drive engineering. 2001 № 2 C. 14–17.

6.2 Valve-inductor motor

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] V	>7	
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% V	
Design tools Maturity TODAY	In house academy	General Available V	Commercial	
A/C level impact : integration synergy potential		V		
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23 V	Special Condition CS23 / CS 25	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	NA
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase V	High Increase	
Price Point	No change / Minor Increase	Medium Increase V	High Increase	Why? What material needed? Etc.

6.2.2.1 Modular scalable electrical energy converters

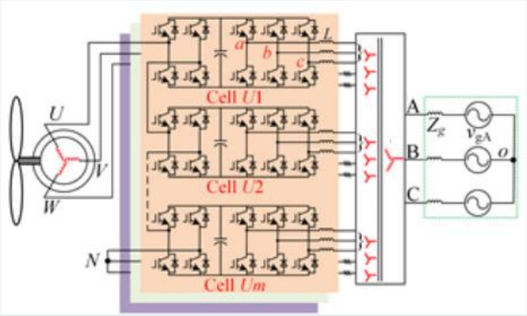
Brief Description

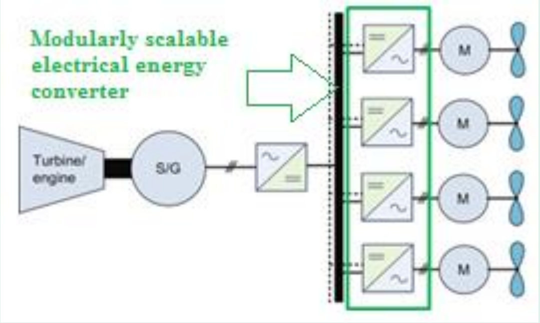
Modularly scalable power converters are designed to build easily scalable modular power conversion systems that provides high reliability, simplicity and ease of maintenance under the control of a single controller.

To implement this technology, it is necessary to use integrated power modules in the development of aircraft power converters.

The power module should allow converting energy in two directions in order to implement the main mode - the operation of motors to create thrust, as well as for the mode of harvesting energy when taking energy from the motors when airplane has flight like descend.

Pictures





Technical Data

The ability to increase the required power

Higher power density

Higher reliability

Mutual reservation

Possibility of flexible variation of installed power

Benefits/Synergies

- Lower manufacturing cost
- High maintainability

Drawbacks

- Complexity
- Environmental-unfriendly
- High specific mass

- References
- CORDIS RCN: 217513 (https://trimis.ec.europa.eu/project/aircraft-modular-power-converter-solutions#tab-outline)
- Alzola, Rafael Pena; Gohil, Ghanshyamsinh Vijaysinh; Mathe, Laszlo; Liserre, Marco; Blaabjerg, Frede/ Review of modular power converters solutions for smart transformer in distribution System
- A. Stepanov, L. Biesenieks, A. Sokolovs, I. Galkin. Development of a Modular Power Converter. Riga Technical University/Institute of Electrical Engineering and Industrial Electronics
- Reznikov S. B., Kiselev M. A., Moroshkin Y. V., Mukhin A. A., Kharchenko I. A. Combined electric power complex modular and scalable architecture for all-electric aircraft electric power systems. State Institute of Aviation Systems

6.2.2.1 Modular scalable electrical energy converters

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6]	>7 ✓	Tests needed
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% ✓	
Design tools Maturity TODAY	In house academy	General Available ✓	Commercial	
A/C level impact : integration synergy potential			✓	Any electrical system
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23	Special Condition CS23 / CS 25 ✓	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	NA
Operations impact	No change	Medium ✓	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase ✓	High Increase	High power semiconductors
Price Point	No change / Minor Increase	Medium Increase ✓	High Increase	Why? What material needed? Etc.

6.2.2.2 Information interaction through power (PLC-technology)

Brief Description

The integration of systems and units provides for close cooperation in the development of a platform that includes systems such as flight control, hydraulic, fuel, air conditioning systems, power supply systems, gas turbine, including information interaction.

The use of communication technology over power lines for data transmission over a high-voltage DC network for functional systems makes it possible to increase the degree of integration of information and functional systems.

The PLC communication approach eliminates the need for digital data bus wiring by modulating data on power cables that run between the flight control computer and the control devices.

Aviation PLC technology is optimized to meet the needs of the aviation world: strict deterministic and reliable communication, environmental conditions relative to RTCS-DO 160, and filtering and data transfer functions

Pictures

Technical Data

The minimum cyclic prefix duration is 5.56 µs

Delay spread 100ns

Speed 200 Mbit/s in the [1;30] MHz bandwidth

Coherence bandwidth [0.6;0.9] MHz

Support of deterministic, segregated, and configurable communication (100 Mbit/s and more are possible)

Reduced cabin data networks (< 30%)

Support of any digital data communication (e.g. Ethernet, CAN, ARINC429)

Benefits/Synergies

- Fewer data cables, weight and volume
- Less complex architectures
- Reduced installation effort
- Reduced operating costs (e.g. fuel, installation, and maintenance)
- intelligent energy distribution

- References
- T. Larhzaoui, F.Nouvel, J-Y Baudais. OFDM PLC transmission for aircraft flight control system.
- P. Tanguy and F. Nouvel, ”In-vehicle PLC simulator based on channel measurements,” International conference on intelligent transport system telecommunication (ITST),2010 , pp. 1-5.
- M. Šegvić, K. Krajček and E. Ivanjko, “Technologies for distributed flight control systems: A review,” in 38th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, 2015.

6.2.2.2 Information interaction through power (PLC-technology)

Quick Assessment Sheet	Low	Medium	High	Comments
Technology Readiness Level (TLR) TODAY	[1-3]	[4-6] V	>7	Widely used in electrical industry
Probability of Technology Readiness Level 6/7 in 2030	< 35%	35% < P < 65%	> 65% V	
Design tools Maturity TODAY	In house academy	General Available	Commercial V	
A/C level impact : integration synergy potential		V		Any functional system
Regulatory Status Readiness / Maturity TODAY	No or just working groups	GA or CS23	Special Condition CS23 / CS 25 V	
Consortium Experience TODAY				What is the experience level of the consortium?
Maturity for circular economy / Life Cycle @ EIS				Life cycle duration and maturity for circular economy are connected: short lifetimes means higher replacement rates and increased recycling
Potential for diminishing emissions	Low / Indirect	Direct	High	NA
Operations impact	No change	Medium V	Paradigm Shift	
Complexity	No change / Minor Increase	Medium Increase V	High Increase	Transmitter/Reciver
Price Point	No change / Minor Increase V	Medium Increase	High Increase	