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Aircraft Design Implications of Alternative Fuels for Future Hybrid-Electric Regional Aircraft Configurations

Jonas Mangold, Felix Brenner, Nicolas Moebs and Andreas Strohmayer
University of Stuttgart, Institute of Aircraft Design
Pfaffenwaldring 31, 70569 Stuttgart

Abstract

Air transport is a driver of economic prosperity, as it connects millions of people and provides a fast way to travel. However, the environmental impact, such as emissions like carbon dioxide, nitrogen oxides or noise, is more and more in the focus of the broad public. Electrification of the powertrain can offer advantages over conventional architectures, as electric components operate at higher efficiencies and have a higher specific power compared to combustion engines. This adaptation could enable novel propulsion concepts, such as distributed electric propulsion.

An all-electric aircraft would produce no in-flight emissions, but remains limited in range due to the low specific energy of current battery technology. A hybrid-electric propulsion system could compensate for this disadvantage. Combining a conventional primary energy source (combustion engine) with the electrified powertrain can increase the range compared to an all-electric design and still can reduce emissions compared to conventional aircraft. However, to limit the environmental impact, alternative fuels are necessary for an environmentally friendly hybrid-electric propulsion concept.

Sustainable Aviation Fuels (SAF), Hydrogen (H2), and also Methane (CH4), are the most promising fuels to further greening transportation and aviation. It is quite evident that hybrid-electric propulsion and alternative fuels have a substantial effect on the aircraft configuration. In this respect, SAF could be an intermediate CO2-neutral solution, as only small changes to aircraft and airport infrastructure are required. In contrast, fuel tanks and related systems would significantly change for Liquid Hydrogen (LH2) and Liquid Natural Gas (LNG).

The Horizon 2020 research project FUTPRINT50 (“Future Propulsion and Integration: Towards a Hybrid-Electric 50-Seat Regional Aircraft”) analyzes potential future hybrid-electric aircraft configurations in depth, not only assessing the required technologies, but also the use of different forms of energy storage, in particular alternative fuels. The focus of this paper is on the impact of these alternative fuels on aircraft design.

1. Introduction

The positive societal effect of aviation due to its ability to connect regions, transporting people and goods with short travel times, is uncontested. However, given the global challenge of reducing greenhouse gas emissions, the air transport system has to dramatically reduce its environmental footprint. Disruptive change is requested towards a new generation of aircraft with significantly reduced emissions in the near future. This is particularly challenging, as aircraft design is extremely sensitive to any mass increase as well as to safety aspects which might be related to the introduction of new technologies.

In this context, the goal of the Horizon 2020 project FUTPRINT50 is to prepare grounds for a more environmentally sustainable aircraft with a hybrid-electric powertrain, accelerating the Entry-Into-Service of such an aircraft by 2035/2040. The top-level aircraft requirements (TLARs) have been defined with a payload of 50 passengers, a design range of 400 km and a maximum range of 800 km [1]. Additionally, reducing carbon dioxide (CO2) and nitrogen oxides (NOX) emissions by more than 75% and 90%, respectively, and cutting noise emissions by 65% compared to today’s aircraft in this market segment. As can be seen in Figure 1, electrified propulsion, thermal management and energy harvesting have been identified as key-enabling technologies for this design target. In turn, the means of on-board energy storage at the core of an electrified powertrain is a key driver for the viability of a future hybrid-electric aircraft design.

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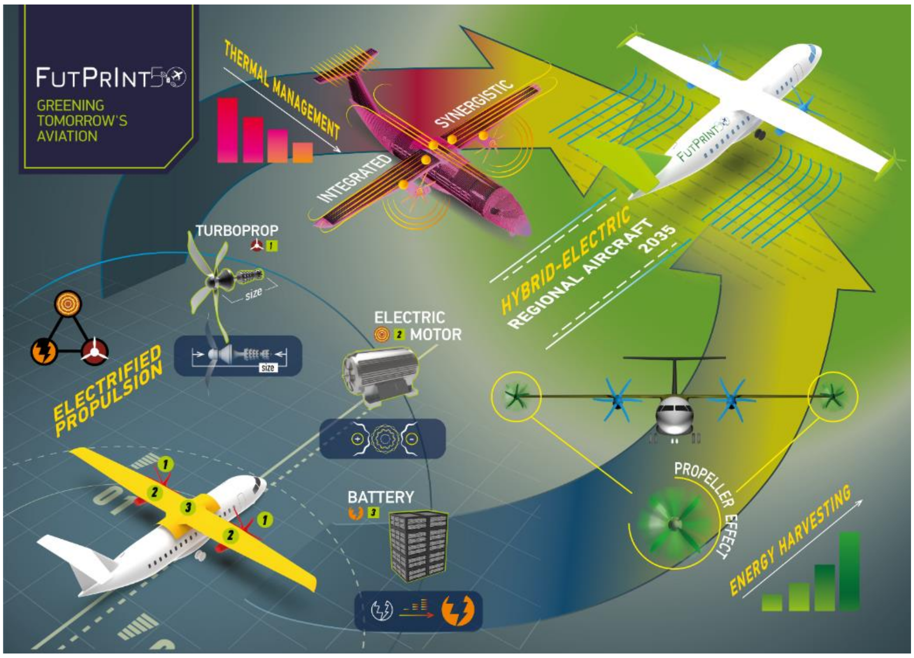

Figure 1: Key technologies within FUTPRINT50

An energy storage concept fully relying on batteries would obviously eliminate in-flight emissions, however, due to the very limited specific energy of today’s battery chemistries, this path remains limited to small aircraft with short ranges. For the TLARs given in FUTPRINT50, a hybrid-electric powertrain architecture with an on-board energy conversion from fuel to electricity therefore seems by far more promising. Considering the environmental challenge, this fuel imperatively has to be non-fossil, so alternative fuels such as SAF, hydrogen and methane attract the attention of aircraft design.

The use of SAF would leave the engine and the fuel system mostly unaltered, as the same properties of SAF and Jet A-1 are targeted. This is an advantage, as it basically allows conventional aircraft engines to be used, enhanced by hybridization. H2 has apparent benefits as a fuel for aviation due to its higher specific energy compared to kerosene. On the other hand, H2 requires more storage volume due to its much lower density. In FUTPRINT50, several powertrain architectures and corresponding aircraft configurations are investigated, looking at both SAF and liquid hydrogen (LH2) as primary energy carriers. A possible arrangement of the LH2 tank aft of the rear pressure bulkhead can be a reasonable solution. However, in terms of aircraft design, this can for example affect the aircraft's stability and increase trim drag. Thus, the empirical knowledge based on classical designs can no longer be generally applied to such configurations, and the design methodology has to be adapted. Combined with the variations of energy management strategies, this results in many new open variables, but also opportunities to reduce emissions in the different flight segments. Methane could serve as an additional fuel for future aircraft configurations as an intermediate stage to LH2.

While various conceptual aircraft design studies have been made to date for different fuel options, this work provides a systematic comparison of the implications of different fuels on the related optimized aircraft configuration. All designs correspond to a given set of TLARs and the design impact is derived from fuel properties, but also taking into account the constraints imposed by fuel systems integration and considering operational aspects in the concept evaluation. Regarding this design evaluation, it becomes evident that direct operating costs as today’s standard figure of merit does not satisfactorily cover environmental aspects, at least as long as emission curfews are not imposed on a worldwide basis. Therefore, the paper concludes with a new figure of merit metric, which also covers environmental aspects and technological risks in a holistic design evaluation.

2. Properties of Alternative Aviation Fuels

This chapter introduces the properties of fuels and energy sources relevant for future aircraft configurations. Firstly, the differences and similarities between Jet A-1 and the carbon-neutral SAFs are evaluated. Secondly, the advantages

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and disadvantages of hydrogen are investigated, especially the density and the specific energy in different physical phases. Finally, methane will be elaborated as a potential intermediate stage between SAF and hydrogen.

2.1 Jet A-1 and SAF

Modern jet aircraft today primarily use Jet A-1 fuel. This is due to a high volumetric energy density and a wide liquid state temperature, ranging from –47 to +38 °C [2]. At international standard atmosphere sea level conditions, typical Jet A-1 fuel has a gravimetric energy density of 43.2 MJ/kg at 775–840 kg/m^3 [2,3]. The terms gravimetric energy density, specific energy and the lower heating value (LHV) are synonymous and indicators for the combustion and power supply process and refer to the useable energy. The resulting volumetric energy density is 33–36 MJ/l. These properties of Jet A-1 are convenient in today’s aircraft operational environment, since the fuel can be stored inside the wings without a need for complex and heavy insulation or temperature control.

Fuels used in aviation must display a particular set of properties [4]: High volumetric energy density, high specific energy, high flash point, high thermal stability, good lubrication properties and sufficient aromatic compounds. Main chemical components of Jet fuel are alkanes, isoalkanes, cycloalkanes and aromatic compounds [4]. The high hydrogen-to-carbon ratio of the alkanes ensures that the fuel has the required energy density. Cycloalkanes help to reduce the freezing point and the presence of aromatics improves the lubricity of the fuel, also ensuring the function of seals and O-rings to prevent fuel leakage [4].

In aeronautics, the fuel used is not only the energy carrier, but it is also a significant component in heat exchange and mass balance for various conditions and altitudes [5]. Therefore, very strict physical standards are specified for production [5].

SAFs are a broad definition of drop-in kerosene alternatives produced from a variety of feedstock [4,6]. Among those, biofuels and synthetic fuels are the most promising ones [7]. Biofuels can be produced from any renewable carbon-based material and are therefore part of the associated carbon life cycle [6]. On the other hand, synthetic fuels do not rely on biomass and can be produced for example with the Fischer-Tropsch pathway [4,5,6]. Power-to-liquid fuels require CO2 and H2 [6], where environmentally friendly the CO2 is captured from the air and H2 is obtained through electrolysis from water. Depending on the production methods, the environmental impact of different SAFs may be significant [8]. In their chemistry SAFs are very similar to conventional jet fuels [9]. The properties like density, flashpoint, heating value and viscosity of SAF and Jet A-1 vary to some extent between the different existing and potential aviation fuels [5]. However, the values are in the same order of magnitude and are technically suitable [5].

SAF have the ability to reduce the carbon footprint of aviation significantly if produced at a high enough capacity [10]. Today’s production volume of SAF is rather low and energy intensive [11]. However, they should be produced using renewable energies. Recent in-flight studies show, that SAF cannot only reduce carbon emissions, but may also reduce the formation of contrails significantly [11].

For the whole flight envelope, aviation fuels must ensure a safe and reliable operation [5], with two specifications primarily used worldwide [5], ASTM D1655-09 and Def Stan 91-91, to be fulfilled for certification. Not only the fuel, but also the fuel system, including materials and sealings are important for a certification [5]. Nitrile O-rings require a level of aromatic content for a proper function [4,6,12], which shows the dependencies and requirements on future aviation fuels. Also, engine failure and erosion can be problematic for operations with SAF [12]. Despite these challenges, some successful demonstration flights show the usability of SAFs [13].

2.2 Hydrogen

In the transportation and energy sector, hydrogen is of high interest today, in particular as the molecule does not contain any carbon atoms, which thus will not pollute the environment with carbon emissions; at the same time the gravimetric energy density is very high (120 MJ/kg) [14]. Despite the high gravimetric energy density, the volumetric energy density of LH2 is low. At ambient pressure, the normal boiling point of hydrogen is 20 K [15]. At atmospheric pressure, the density of LH2 at saturated state is 70.8 kg/m^3 [15,16]. This results in a volumetric energy density of 8.5 MJ/l. The energy density of hydrogen including different pressure levels is shown in Figure 2.

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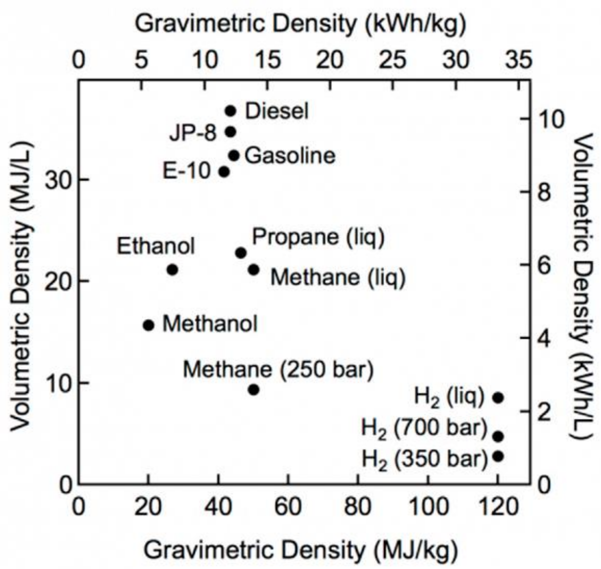

Figure 2: Energy densities of different fuel options [14]

The gravimetric energy of hydrogen is not a function of the phase state, and therefore does not differ from pressurized hydrogen to LH2. On the other hand, the volumetric energy density is related to the phase state of hydrogen, being significantly higher for LH2 compared to pressurized hydrogen. In comparison to SAF, the volumetric energy density of LH2 is four times lower. Therefore, only LH2 seems feasible and suitable for commercial competitive aircraft because otherwise the volume and mass of the tank would be too great. Additionally, a further subcooling of LH2 is required for the refueling process, increasing the volumetric energy density [17].

The main emission when burning LH2 in a combustion engine or using it in a fuel cell is water [18]. Due to the high combustion chamber temperatures, besides water vapor, nitrogen oxides will be emitted when burning [19]. In terms of engine exhaust emissions, hydrogen is carbon-neutral.

Problematic today is that less than 1% of all hydrogen produced is so-called “green” hydrogen, i.e. hydrogen produced using only renewable energies like solar or wind [20]. Most hydrogen today is produced from steam reforming or partial oxidation of hydrocarbons [21]. As mentioned before, it is paramount that the production of future aviation fuels and SAF is based on environmentally friendly, renewable energy.

To store hydrogen in its liquid state at near atmospheric pressure, several aspects of the molecule need to be considered. Hydrogen is highly volatile, therefore special metal liners are required to prevent leaking [22]. In some cases, hydrogen will permeate into the surrounding metal and cause embrittlement [23]. Metals typically used for cryogenic hydrogen tanks are made of steel or aluminum [22]. To maintain a liquid phase in the tank for long periods, typically vacuum or double-walled insulated tanks are used [22], because of the high temperature difference to the ambient atmosphere. Foam insulations are also possible resulting in a lower tank mass and less insulation [24].

2.3 Methane

Methane (CH4) is the shortest-chain hydrocarbon naturally occurring [25], composed of four hydrogen atoms and one carbon atom. Methane is the main component of natural- and biogas [25]. Gas of both origins is used as an alternative fuel in the automotive and marine sector today [26]. While CNG is an applicable option for smaller vehicles, larger means of transportation like ships or trucks require liquified natural gas (LNG) to minimize the fuel tanks mass and volume [27]. Through cryogenic liquification the volumetric energy density of methane is increased by a factor of 600 [27].

Compared to conventional fuels, fossil methane emits 25% less CO2 in direct combustion [28], by the difference in chemical formula and the number of carbon atoms. Methane obtained from biomass (waste and manure) however emits net-zero CO2 [28]. Another possible form of renewable natural gas (RNG) is green hydrogen combined with carbon captured from the atmosphere [29]. In addition to being low in carbon, methane is the cleanest burning naturally occurring gas [30]. It typically burns completely soot free and reacts with oxygen to two water molecules and one CO2 molecule [30]. This clean burning behavior makes methane an interesting candidate as an alternative aviation fuel.

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Since fewer particles are emitted, the formation of contrails and aviation induced cirrus clouds is expected to decrease by around 50% [28]. Both have a significant share of approximately 60% of the relative radiative forcing effects attributed to aviation [28].

With a volumetric energy density of 21 MJ/l the storage tanks for LNG require less than half the volume of LH2 tanks for the same amount of energy [14]. The gravimetric energy density of CH4 (49 MJ/kg) [14] is lower than that of LH2 (120 MJ/kg), but slightly higher than that of conventional Jet A-1 fuel (43.2 MJ/kg). The relations of the gravimetric energy density and volumetric energy density for different fuels including CH4 are also shown in Figure 2. Furthermore, the normal boiling point of CH4 is around 112 K, which is around 90 K higher than what is required for H2 [16]. The insulation material thickness and ultimately tank size and mass can therefore be reduced.

Methane can be co-burned with kerosene or SAFs in slightly modified jet engines [28]. Especially in an early transition stage, this could be a great advantage as from the start LNG will not be available at every airport. In contrast to hydrogen, gaseous methane (of any origin) can be distributed through existing natural gas pipes [28]. Additionally, the worldwide LNG infrastructure is currently strengthened to compensate Russian gas imports [31]. This could provide a good starting point for a transition to LNG as an aviation fuel in the near future.

3. Aircraft Design Implications

The properties of future aviation fuels have a direct impact on the overall aircraft design. The sizing and dimensioning of the aircraft becomes challenging and requires, especially for hybrid-electric aircraft, new methods and tools. This chapter describes the conceptual sizing of an aircraft design adapted to different fuels and their properties and shows the resulting hybrid-electric configuration.

3.1 Initial Sizing of Aircraft with the Breguet Equation

Conventional combustion aircraft are usually sized with the Breguet equation, see Equation 1. The propulsive efficiency η_{Prop} and the power specific fuel consumption SFC determine the efficiency of the propulsive system. The term L/D defines the aerodynamic efficiency and the logarithmic mass decrease takes the fuel burn into account. Those factors are the main variables for the calculation of the aircraft's range R.

$$R = \frac{\eta_{\text{Prop}}}{SFC} \cdot {}^{L}\!/_{D} \cdot \ln\left(\frac{1}{1 - {}^{m_{\text{Fuel}}}\!/_{m_{\text{TO}}}}\right) \tag{1}$$

The SFC is related to a particular fuel and provides information about the efficiencies of the power source $\eta_{\text{PowerSource}}$ and integration η_{Int} and the energy density $E_{\text{s,Fuel}}$ (Lower Heating Value) of the energy supply. For propulsion architectures which lose mass during the flight, i.e. exhausting the combustion products, Equation 2 can be used as a more general equation, related to different propulsion systems and fuels.

$$R_{\text{Fuel}} = \eta_{\text{Prop}} \cdot \eta_{\text{Int}} \cdot \eta_{\text{PowerSource}} \cdot \frac{E_{\text{s,Fuel}}}{g} \cdot {}^{L}\!/_{D} \cdot \ln\left(\frac{1}{1 - {}^{m_{\text{Fuel}}}\!/_{m_{\text{TO}}}}\right) \tag{2}$$

By splitting the SFC into different efficiencies, it is possible to look at the advantages and disadvantages of different fuels in combination with the power source: Firstly, a look at the energy content of the three different fuels laid out in Section 2: Methane has a 13% higher gravimetric energy density than SAF. In contrast, hydrogen has a clear advantage with a factor of 2.8 in energy content compared to SAF. Taking the energy density linearly into account in the range calculation, hydrogen has an advantage over SAF and methane. This means that for a given range, hydrogen and methane have a lower fuel mass compared to SAF, which in turn positively affects the range calculation.

Secondly, the lower fuel mass for the same energy means that the fuel mass fraction ($m_{\text{Fuel}}/m_{\text{TO}}$) decreases. In logarithmic terms, however, a decreasing mass fraction means a shorter range because the aircraft exhausts less mass and is therefore heavier at the end of the mission, requiring more propulsion power. This effect consequently enters the Breguet equation for a growing fuel mass ratio in an exponentially increasing manner. In other words, the more mass an unchanged aircraft loses during the mission the farther it can fly. In this respect, hydrogen has a significant disadvantage over SAF, and methane in this consideration due to its high LHV. However, an accurate comparison of

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the logarithmic fuel mass ratio cannot be made at this stage, as this would require a complete preliminary aircraft design to determine the take-off mass and the required fuel mass.

Thirdly, the power generation efficiency is to some extent in the same region of about 55% [32,33,34,35,36] for all three fuels regardless of the energy conversion process, i.e., combustion or conversion by fuel cell. Thus, the power source, integration and propeller efficiencies do not offer much difference between power generation methods.

The use of a fuel cell, battery or electrified propulsion, on the other hand, fundamentally changes the propulsion concept and creates a hybrid-electric powertrain. The hybrid-electric powertrain facilitates unconventional propulsion and aircraft configurations. Disruptive propulsion concepts like wing tip propellers or distributed propulsion systems cannot be realized with internal combustion engines without incurring significant drawbacks. Equation 3 shows the range formula for battery-electric propulsion. In this case, the efficiency of the electric motor (about 95% [37]) is much higher than the efficiency of small combustion engines just in a range of 35–40% due to their low overall pressure ratio and the turbine entry temperature [38]. In addition, the unconventional arrangements of the propellers, for example, offer further aerodynamic advantages. This can be used to increase not only the propeller efficiency, but also the glide ratio [39]. On the downside, batteries have a low specific energy, which is a factor 45 lower compared to SAF and even a factor 130 lower compared to hydrogen. As a result, with today’s state-of-the art battery chemistries, ranges above 500 km cannot be realized with battery-electric regional aircraft, see Equation 3. In addition, battery-electric aircraft (lithium-ion) do not have the advantage of losing mass during the flight mission and thus carry the battery mass with them over the entire mission. While fully emission-free, due to these adverse factors only about one third of the range of an SAF-powered aircraft can be achieved with a battery-powered aircraft in the best case [40].

$$R_{\mathrm{Battery}} = \eta_{\mathrm{Prop}} \cdot \eta_{\mathrm{Int}} \cdot \eta_{\mathrm{EM}} \cdot \frac{E_{\mathrm{s,Battery}}}{g} \cdot {}^{L}\!/_{D} \cdot \left(\frac{m_{\mathrm{Battery}}}{m_{\mathrm{TO}}}\right) \tag{3}$$

To compensate for the disadvantage of the low specific energy of batteries but still retaining the advantage of high propulsion efficiency, a hybrid-electric powertrain is necessary. Possible architectures are turboelectric, parallel or serial hybrids. By combining the energy conversion of a future aviation fuel with high specific energy with an electrified powertrain, energy demand and emissions can be reduced [41,42]. In this case, the Breguet equation shown above can no longer be used for range calculation, as power is provided by different energy sources. Thus, a numerical differential method must be applied, which solves the equations of motion on a pointwise basis. The required thrust is thereby provided by summing up the thrust of all propellers, which can have different power sources. The power split between conventional engines and electric motors is defined as the hybridization degree of power. The energy management strategy (EMS), which reflects the use of the combustion engines, thus has a major influence on the design and power split for the overall mission. For example, an EMS that uses only the internal combustion engines in cruise flight results in a low battery mass and hence a lower take-off mass. The sophisticated use of combustion engine and electric motors can be seen already in the sizing chart in a conceptual design cycle [43]. By activating the electric motors during take-off and climb, a smaller combustion engine can be installed.

In the research project FUTPRINT50, several configurations are investigated, which differ in the type of fuel and the hybrid-electric propulsion architectures [42]. The most promising configurations are explained in the following sections. For the calculating, sizing and dimensioning of the future hybrid-electric regional aircraft, the conceptual aircraft design environment SUAVE is used [44]. The feasible implementation of different power networks enables the possibility of comparing the aircraft and the interaction between the key technologies.

3.2 Parallel Hybrid-Electric Configuration with SAF

In a first parallel hybrid-electric architecture, two turboprop engines are fed by SAF tanks. A gearbox connects the propeller shaft not only to the engine but also to an electric motor [42]. Thereby, the electric motors can support with an additional share of power during high-power flight missions like take-off or climb. This allows the turboprop engines to be downsized, which can save mass and costs. Two more electrically driven propellers are installed at the wing tips, so-called wing tip propellers (WTP). Those propellers can lead to aerodynamic improvements as they interact in a positive way with the vortex at the wing tip which normally induces drag [45]. All electric motors are mainly powered by battery packs. However, electric power generation by the turboprops and wing tip propellers through generators is also possible. A scheme drawing of this powertrain is shown in Figure 3.

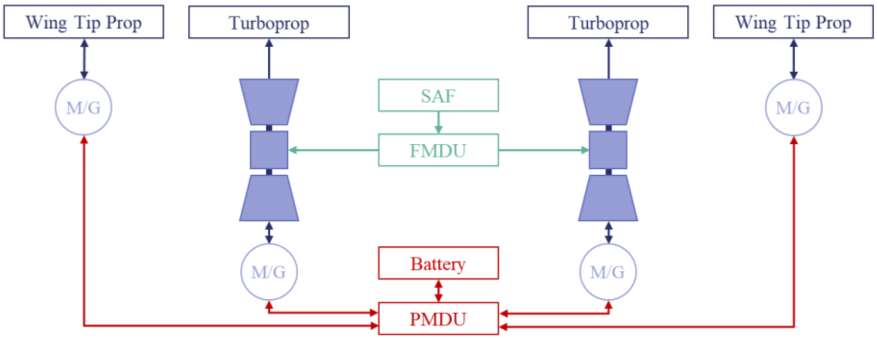

Figure 3: Parallel hybrid-electric propulsion architecture

The aircraft configuration is realized as a high-wing 50-seat regional propeller aircraft (see Figure 4). In this architecture, the battery is placed in the belly of the aircraft, close to the center of gravity. As known from conventional aircraft, the SAF tank remains in the wing. All propulsors are thought to be running during all airborne flight phases. The parallel hybrid propulsion architecture changes the aircraft configuration only minimally. By using SAF as the primary energy source, the fuel and refueling system does not change, focusing the development efforts primarily on the hybrid-electric propulsion system.

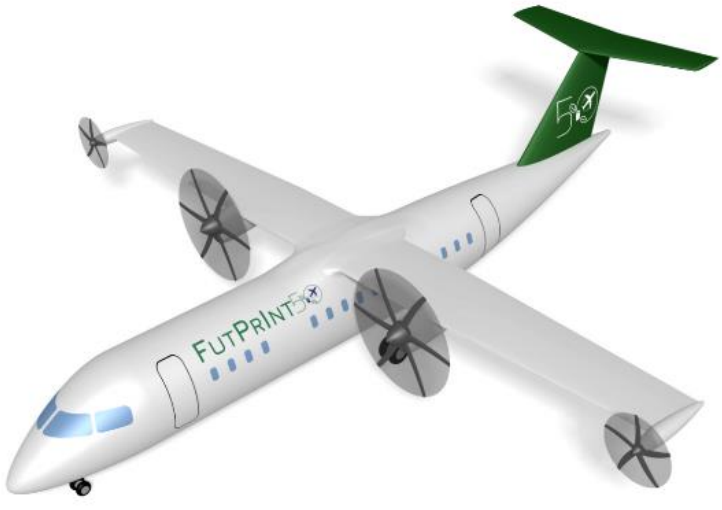

Figure 4: Parallel hybrid-electric configuration with SAF

Initial design results show the potential of this propulsion configuration, which requires less fuel and thus results in less emissions compared to a conventional aircraft [42]. However, the total energy taken from fuel and battery is still higher [42]. An optimized EMS [46] offers a further improvement, translating to fuel and energy savings. For hybrid-electric aircraft, the exact power split between the various energy sources and propulsors in different flight segments is defined by the EMS and must be managed by complex optimization solvers. However, the combination of hybridization with an optimized EMS does not yet provide a functional aircraft, other aspects such as the thermal management system also come into the foreground. Due to the relatively low temperatures of the electric components compared to a combustion engine and therefore a significantly lower delta in temperature, their cooling is no longer trivial. Several cooling options are conceivable, such as through a skin heat exchanger or a liquid vapor cycle [47]. For the aircraft design, this additional system requirement means an increase in mass, required power and additional drag related to cooling.

Due to the almost identical properties of SAF compared to Jet A-1, the use of SAF does not involve significant risks. By hybridizing the powertrain, additional synergies can be generated, leading to further advantages in emissions and the energy required. In addition, all-electric aircraft with smaller ranges are already proven, making the conversion to the hybrid-electric powertrain more feasible. Thus, the transition to a carbon emission-free aircraft bears a low risk and, therefore, does not require high development costs.

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3.3 Cryogenic Configurations

For the application of cryogenic fuels, LH2 and LNG, the tank and fuel system in particular must be adapted. Due to the low temperatures, every component in contact with the fuel must be insulated to prevent heat input. Any heat input would lead to evaporation and, finally, to a loss of fuel. The tank, which depends on the aircraft size and design requirements, can no longer be reasonably placed in the wing [24], has a significant role in aircraft design for cryogenic fuels as it involves a major mass increase. The gravimetric index GI describes the fuel mass in relation to this system mass including the fuel:

$$GI = \frac{m_{\text{Fuel}}}{m_{\text{Tank}} + m_{\text{Fuel}}} \tag{4}$$

Studies for LH2 assume a GI between 25% and 35% [18,48]. For LNG, the GI should be larger as the insulation can be thinner due to the smaller temperature difference. For aircraft LNG tanks, a gravimetric index of 83% is assumed [49]. This might be a rather optimistic estimation compared to the mass of LH2 tanks. However, LNG tanks are generally more simplistic compared to hydrogen tanks. This is because the operating temperature is much higher, and hydrogen embrittlement does not need to be considered in the material selection.

Conversely for LH2, this means that the additional tank mass is larger than the fuel mass required. For a meaningful comparison between the different cryogenic fuels, the system mass including the fuel mass is relevant. To account for this additional mass, the specific energy alone is not representative. The system-specific energy $E_{\text{s,system}}$ results by relating the stored energy to the total system mass. Therefore, the specific energy of the fuel can be reduced by the GI to allow comparison of total system masses. This results in the system-specific energy $E_{\text{s,system}}$:

$$E_{\text{s,system}} = \frac{E}{m_{\text{Tank}} + m_{\text{Fuel}}} = E_{\text{s}} \cdot GI \tag{5}$$

For a comparison of the different future aviation fuels, $E_{\text{s,system}}$ provides a new parameter that also covers aircraft integration. For SAF, the $E_{\text{s,system}}$ will not change from E_{s} as the integral tank in the wing typically has no additional mass. The $E_{\text{s,system}}$ for hydrogen results to 42 MJ/kg with a GI of 35%. This value is in the same order of magnitude as SAF, no longer showing a significant advantage in mass. For LNG, a similar system-specific energy of 41 MJ/kg with a GI of 83% can be calculated.

In conclusion, this means that with respect to the tank system mass, all three alternative aviation fuels have the almost the same $E_{\text{s,system}}$. So other aspects like emissions will become more important when assessing the potential of alternative fuels. Further research and development in tank materials, design and construction could improve the results to the advantage of cryogenic fuels.

3.3.1 Liquid Hydrogen – Combustion Engine vs. Fuel Cell

The liquid hydrogen propulsion architecture shows a further possible power source through the use of a fuel cell and electrolysis. Direct combustion of hydrogen is the second option here, with previous studies showing that conversion of the Jet A-1 engine to hydrogen is possible [24]. The Tupolev 155 [50] was a partially LH2 powered aircraft already in the 1980s. A characteristic feature was the chimney above the vertical tailplane, which was used for safe venting of gaseous hydrogen.

The primary advantage of a combustion engine using hydrogen is that also a conventional (non-hybrid-electric) propulsion concept can be implemented. Thus, the development risk and cost of a hybrid concept would not occur, and carbon emissions are eliminated at the same time. However, as already shown in Section 3.2, the parallel hybrid-electric powertrain can have advantages regarding the dimensioning of the individual components and could also operate with direct hydrogen combustion. The development risks and costs are high in regard to the changes in fuel and tank system. Through the almost unchanged combustion engine, the propulsion concept seams feasible. However, this architecture will not be further considered in more detail in this paper due to the NOX emissions resulting from the combustion.

The LH2-powered configuration under consideration features a serial hybrid-electric architecture, see Figure 5. One or more fuel cell stacks serve as the primary power source. This electric power drives many propellers that are

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distributed alongside the leading edge of the wing, so-called distributed electric propulsion (DEP). As the integration of the LH2 fuel tank and distribution system requires major changes to the entire aircraft configuration, an increase in empty mass and volume, and therefore drag, is expected. Furthermore, batteries are installed to give reserve power during high-power segments and, more importantly, during transient (dynamic) changes in power.

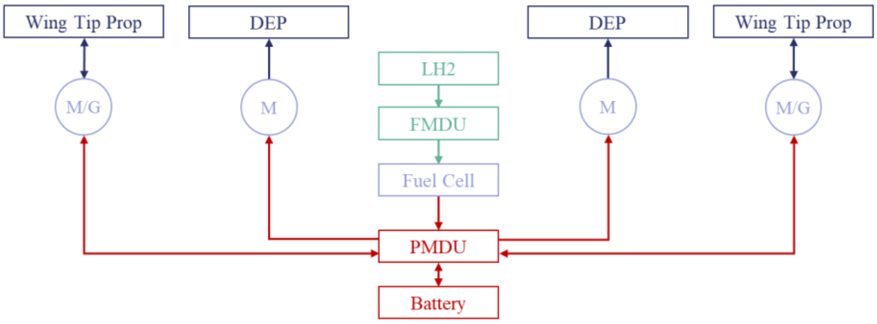

Figure 5: Serial hybrid-electric propulsion architecture with LH2 fuel cell

Current studies suggest placing the LH2 fuel tank in the aft of the aircraft [52,53]. In Figure 6, it becomes apparent that this leads to a substantial increase in wetted area of the fuselage. Due to the use of DEP, however, the wing area can be significantly reduced as this can be compensated by the increased dynamic pressure induced by the propeller wash alongside the entire wing span. The resulting lower drag offers the potential to save energy during cruise. The fuel cell hybrid-electric configuration enables zero-emission aircraft. Therefore, it is one of the most promising architectures for environmental aviation. A disadvantage is the low readiness level of the fuel cells for higher power settings in combination with the heavy LH2 tank. This combination results in the highest development costs and risks.

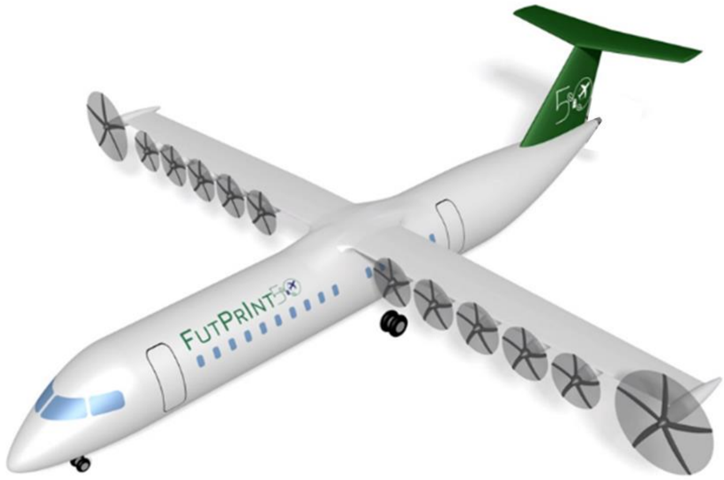

Figure 6: Serial hybrid-electric configuration with fuel cell and liquid hydrogen

For both, fuel cell and direct combustion engine, there is the need of feeding gaseous hydrogen into the power source [24,51]. Therefore, the LH2 has to be vaporized before the engine, which requires additional energy input. In theory, two options to feed hydrogen from the tank to the engine are conceivable, which depend on the sequence of the system components arrangement [17]. The preferable sequence for the transport of LH2 is by a low-pressure pump, high-pressure pump, and subsequent heat exchanger, because of the type of energy required [17]. Through the compression, first the electrical power required for the pump is kept low and the thermal energy from the combustion or electrolysis is used for the LH2 vaporization.

3.3.2 Transfer to Liquid Methane

When designing an LNG fueled aircraft, the following safety aspects should be considered: As with hydrogen, no odors can be added, therefore, leaked methane gas is undetectable by humans [54]. As with other cryogenic fuels, fire and cryogenic burns should be considered [54]. Methane itself is a very potent greenhouse gas [55]. Therefore, leakage must be prohibited to not harm the environment. These safety concerns with LNG require a similar aircraft design as for LH2. A detailed explosion protection concept can be found at Mangold et al. [17].

However, in comparison to LH2, more conventional designs are feasible due to the lower LNG volume. The main differences in aircraft design for cryogenic fuels in comparison with SAF are:

- Accommodation of large cryogenic tanks inside the fuselage (a minimum of two for redundancy and center of gravity adjustments).
- Increased fuselage length for a given payload.
- The wings need to be strengthened due to the increased root bending moment with full tanks. This results in heavier wings in relation to the maximum take-off mass than what is to be expected for conventional aircraft.
- Minor modifications to the engines [28].
- Shielding gas (nitrogen) atmosphere around the fuel tanks and pipes to mitigate the risk of leaked gas explosions.

3.3.3 Further Challenges for Implementation

Compared to kerosene, both LH2 and LNG require an aircraft redesign to assure a high level of safety. If done so, however, the potential of both fuels to reduce the climate impact of aviation is very high. In the 1980s, a Tupolev Tu-155 (a modified Tu-154) flew – with LNG and LH2 as combustion fuels [56]. The Tu-155 conducted around 100 flights, proving the feasibility of cryogenic fuels for aviation [56]. For cryogenic fuels (LH2 and LNG), a similar conclusion can be drawn for aircraft design. Due to the large temperature differences from the environment, strong insulation is needed to prevent losses. This makes the tank heavy and is likely to be placed in the fuselage. In addition, further problems arise that are still research topics and need to be answered: Cavitation at the pumps, material degradation due to thermal cycles, hydrogen embrittlement and diffusion, explosion protection, spills and leakages.

Besides the challenging fuel production, transportation and aircraft implementation, another aspect becomes important for aviation: The airport turnaround and especially refueling. Due to the different physical properties of cryogenic fuels, the conventional refueling procedure is no longer possible. For competitive aircraft, the turnaround must be feasible within 15–20 minutes to keep aircraft utilization high and operating costs low. Especially for LH2, a fast refueling of about 15 minutes is a challenge because the density is much lower, and therefore, a higher volume flow is needed compared to SAF. This fact is not as pronounced with LNG, since the density is only about half of that of SAF. However, both cryogenic fuels are well below the freezing point of water. The temperature difference further creates problems [17,24] such as safe handling by ground staff, the weight of the refueling boom, heat input through the refueling hose, thermal cycles in the hose, and the need for a recovery line. Figure 7 and Figure 8 show two solutions to implement refueling for cryogenic fuels at the airport.

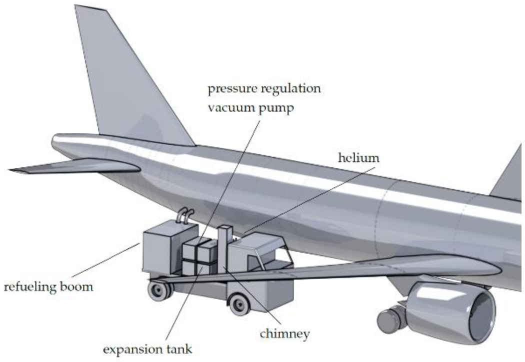

Figure 7: Hydrant dispenser with airport pipeline infrastructure [17]

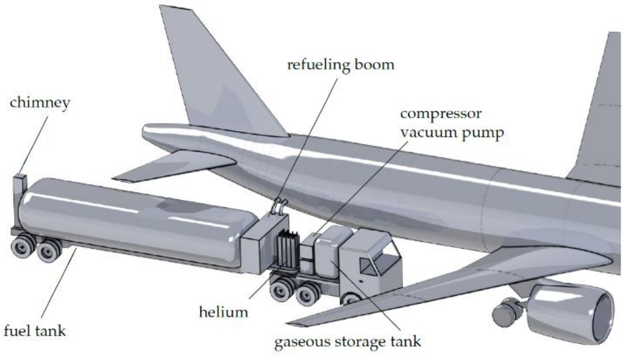

Figure 8: Refueling truck for transition phase between SAF and the cryogenic fuel [17]

These issues can be handled technically and will be feasible [17]. By adapting the refueling procedure, the vehicles, and the airport infrastructure, the duration of refueling is the same and advantageous for regional and short-range aircraft [17]. The methodology of the turnaround and refueling analysis from Mangold et al. [17] can be adapted to LNG, but is not further investigated. The fuel price for future fuels depends mainly on the production and does not depend strongly on influences at the airport [57]. The refueling of cryogenic fuels can therefore be carried out competitively at the airport.

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3.4 Assessment of Future Aircraft Configurations through one Figure of Merit

For decades, most aircraft design handbooks and engineers have seen the direct operating costs (DOCs) as the primary assessment method for aircraft [58,59,60]. As long as the specifications given by the customer are met, this figure serves as a main criterion for airlines to evaluate and compare different aircraft. The DOCs combine many variables that affect the costs that occur in direct context of the operation of the aircraft, like fees, fuel or maintenance costs [61].

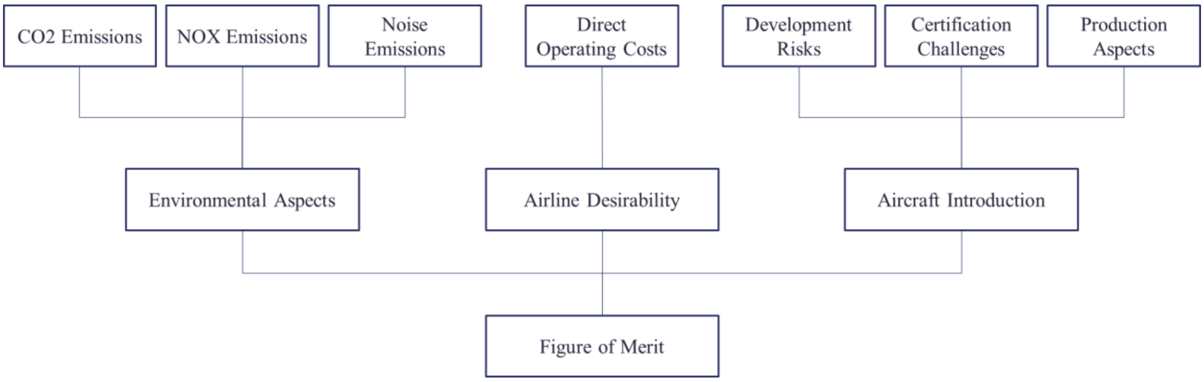

Figure 9: Modular structure of the figure of merit

However, in times of stricter requirements regarding the environmental impact of aviation, other parameters become significant as well. Within the FUTPRINT50 project, seven parameters have been identified to be most influential for the introduction and development of hybrid-electric aircraft [62]. They are shown in the top row of Figure 9. While the DOCs remain an important factor for the airline desirability, additional factors are introduced to represent the environmental and technical challenges.

Especially for future aviation fuels, these alternative assessment methods are essential because fuel emission taxes do not reflect the actual impact on the environment yet. Hence, depending on the propulsion system, the impact and environmental harmfulness or compatibility of an aircraft configuration can be evaluated. Therefore, the Environmental Aspect Index reflects the emissions during the flight mission, which will significantly impact the performance and social acceptance of future aircraft and aviation.

The new fuel, SAF, LH2 or LNG, can also induce changes to the propulsion system and aircraft configuration, as described in the previous section. Therefore, different issues occur, especially for development costs and risks, certification and production, which must be adapted for changed aircraft design conditions. The Aircraft Introduction Index summarizes these three aspects and reflects the extended costs for (hybrid-electric) aircraft designs with future alternative power and energy sources.

All parameters can be weighted accordingly to their impact on the specific evaluations. In order to enable quick assessments, they can be summarized in three overarching categories, which result in one figure of merit. This figure of merit serves as the decisive evaluation measure for future aircraft introducing disruptive technologies to respond to the climate challenge.

5. Conclusion

The implications of alternative fuels on aircraft design are in the focus of this paper. For future hybrid-electric aircraft, the properties of the selected fuel as a means to store the amount of energy required for a defined mission will drive the resulting aircraft configuration together with its respective advantages and disadvantages. In this context, the main goal of alternative fuels is to reduce emissions, while still providing competitive aircraft characteristics for operation and turnaround. Potential alternative fuels could be SAF, LH2 and LNG, all with their specific impact on the components of the hybrid-electric powertrain, the aircraft design and the environmental sustainability.

SAFs offer the most obvious technically feasible solution for future aircraft today, as they have negligibly no impact on aircraft design and configuration. Even the typical tank position in the wing can remain unchanged. However, seals, pipes, and materials have to be adapted to the slightly different SAF characteristics. A disadvantage of SAFs is that despite an environmentally friendly production, their combustion still results in carbon and nitrogen emissions. As part of SAF production, these emissions can be filtered out of the air, but in an energy-intensive process. However, compared to fossil fuels, this carbon neutrality would be a major step forward, together with low development risk and cost.

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The next step towards a more environmentally friendly aircraft would be the use of hydrogen. No carbon emissions result from the combustion process, and in addition, this direct combustion of hydrogen offers the advantage that the engine could remain almost the same. However, fuel lines and tank system would have to change fundamentally, resulting in high project risk and thus development costs. To avoid nitrogen emissions as well as carbon emissions altogether, the propulsion system would have to be switched to a fuel cell as the primary power source. By expanding into a hybrid-electric propulsion system, this development stage can enable zero-emission aviation, only with water remaining. However, with today's state of the art, a fuel cell configuration would come with the highest development risk as the components are still at low technology readiness levels. The use of LH2 requires a thermally insulated tank to be integrated into the aircraft's fuselage or in pods on the wing, resulting in a significant change of the conventional configuration. The additional mass of this tank has a major impact on stability. Therefore, increasing drag needs special attention in the design process.

For liquid methane, similar effects occur for the aircraft design as for LH2. Cryogenic temperatures require insulation and the tank will have to be placed into the fuselage. Nevertheless, LNG offers an advantage over LH2 primarily due to its higher volumetric energy density, reducing the required tank volume by about 50%. As for LH2, the additional fuselage length means additional drag, which must be compensated by a more powerful propulsion system. The development risk could be seen as moderate or high for LNG, as the fuel and tank system also has to be adapted, while not as thoroughly as for LH2. Emissions would be similar to SAF but not as prominent due to the different chemical structure.

As already mentioned, the installation and integration of the cryogenic fuel tanks are the key factor in the upcoming aircraft design process and the aircraft's performance. Therefore, the system-specific gravimetric energy is introduced as a new factor to assess the impact of alternative fuels. This parameter, which combines the tank mass through its gravimetric index and the specific energy of the fuel into one aircraft system. Its comparison shows that all three future aviation fuels in the focus of this paper have a similar value in the region of 42 MJ/kg. This finding means that an assessment based solely on the conventional gravimetric energy density is less meaningful, as it does not consider the related installation effects on aircraft level. All three possible fuels presented in this work therefore have the potential to become main pillars in a future environmentally friendly air transport system. The introduction of the system-specific gravimetric energy density shows the strong dependence on the tank. The gravimetric index of the tank and thus the technical implementation and use of future materials have a sensitive influence on the mass and, thus, the aircraft's performance. Therefore, the further development of the fuel and tank system for cryogenic fuels is essential and requires future research.

Besides the impact on the aircraft vehicle, new fuels also result in changes in the airport infrastructure. Therefore, the turnaround with alternative fuels has to be considered in the assessment of a competitive aircraft design. Especially the refueling process has to be analyzed and extended to cover the different physical properties and related phenomena, also regarding operational safety. The cryogenic temperatures of LH2 and LNG make this turnaround procedure at the airport increasingly complex, while a thorough analysis can show the feasibility within a given turnaround time.

The assessment of the fuels and their impact on the aircraft configurations turns out to be challenging due to the findings so far. A conservative evaluation on the basis of operating costs proves to be limited: With hybrid-electric propulsion, the environmental compatibility and emissions come to the fore, and conversion of these effects into direct operating costs is not always possible nor reasonable. By using a more holistic Figure of Merit, the assessment can be extended in a modular way to cover the environmental aspects dominant today.

Hybridization of the powertrain can provide additional benefits compared to today's conventional configuration. However, the hybrid-electric powertrain components result in new challenges, for example the thermal management system causing additional mass, drag and power consumption. Through a carefully designed interaction of the different components, synergetic effects can be achieved for an improved aircraft performance. In the conceptual aircraft design phase, these benefits can already be highlighted and exploited. The different phases of flight offer the possibility to design powertrain components precisely to the required performance, hence avoiding operating points with lower component efficiencies. During design as well as in operation, an optimized energy management strategy can reduce the amount of fuel and emissions. Here, the challenge for aircraft design is to combine the knowledge and characteristics of different powertrain architectures to create an overall optimized design.

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