ELECTRIC PROPULSION FOR REGIONAL AIRCRAFT- CRITICAL COMPONENTS AND CHALLENGES

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Abstract

This paper describes possible topologies for electric propulsion systems in a regional aircraft; identifies major critical components and challenges concerning their feasibility; and presents a comparison between them. The existing electrified propulsion system topologies can be categorized into all-electric, turbo-electric, and hybrid-electric. These propulsion system topologies are briefly described along with few feasibility studies and examples. Subsequently, key challenges for the electric propulsion system are discussed, focusing on the attributes for low emission, high performance, less complexity and high reliability. This is followed by a detailed explanation of the functions, challenges, and examples from latest developments for the key components. In the final chapter, advantages and challenges in terms of emission, complexity, technology, economic and policy for each topology are summarized.

The topologies in the all-electric category are based on batteries and fuel cells for storing and generating the required electrical energy. Most of the electrical energy is supplied to the electric motors for thrust generation by rotating the propellers. Due to absence of a conventional combustion process, emission reduction goals can potentially be met. Battery and fuel cells are quite efficient at their cell level, but the specific energy density at the propulsion system level drops dramatically, when the necessary structural weight of, for example, their thermal and air management is added. As a result, specific energy density falls below the levels required to enable medium- and long-range flights with average carrying capacity. Additionally, fuel cell and battery systems face challenges in terms of performance, safety, cost, and certification; quick dynamic response; cold condition start; production and supply of hydrogen gas; and integration of large hydrogen gas tanks and battery system on-board of the aircraft. Turbo-electric topologies contain reliable gas turbine-driven electricity generators that offer a high level of safe and certified technology. However, with turbo-electric architectures, it seems difficult to achieve the targeted emission reductions without relying on sustainable and carbon-free aviation fuels from biomass and hydrogen. Direct combustion of hydrogen gas in the combustion chamber is currently at a low technological readiness level. Hybrid-electric topologies are composed of a combination of power generation units from gas turbine and from fuel cell and/or battery systems. They offer low-emission operation during long-range flight phases; and high safety, reliability, and required specific power through gas turbine-based turbo propulsion unit during takeoffs and climbs.

This paper provides an overview of research and developments in electric propulsion technologies and serves as a foundation for future work on a fuel cell-based all-electric topology.

1. MOTIVATION AND APPROACH

Major aviation research and development programs such as NASA's N+3 [1], [2] and European Union's Flightpath 2050 [3] aim to reduce NO_X emission by 90%, CO_2 emission by 75% and noise emission by 65% relative to a civil reference aircraft from the year 2000. A future trend in civil aviation is heading towards electrified aircraft, as they use sustainable energy resources and produce fewer emissions than conventional aircraft with kerosene-fueled gas turbines. Electric propulsion is recognized as key enabler technology with the potential to achieve those targets. As regional aircraft contribute to 50% of fuel consumption and resultant CO_2 emissions of the aviation sector, together with the fact that technology of an electric propulsion for long-range operation is not mature enough, short-haul operation is targeted for the introduction of more electric propulsion technologies [4].

The use of liquid hydrogen as an aircraft fuel in combination with fuel cell technology is recognized as by far the most promising option for achieving the year 2050 goals, as it has potential to reduce fuel consumption by 64.1% [4], [5]. In an electric propulsion system, the thrust-generating components, such as the propeller with an electric motor, are decoupled from the energy generation or storage units, such as generators, fuel cells and batteries. The electrical power can be transported across the aircraft via power lines, enabling distributed propulsion by using multiple smaller propeller units and their novel integration into the airframe. Additional drag reduction can be achieved through the boundary layer ingestion (BLI, air adjacent to fuselage is pulled strongly in order to decrease boundary layer thickness) and retracting the propeller blades during cruise phase [5], [6], [7], [8]. These key advantages of electric propulsion, along with lower emissions over gas turbine-

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driven propulsion systems, onwards also called as turbo propulsion, make it viable for achieving the political and emission goals. In the following chapter, various possible topologies are described in the categories of all-electric, turbo-electric and hybrid-electric. The major functions and challenges are covered in the next section to identify critical technologies for electric propulsion systems. Then, latest developments in main components and the subsystems are explained in detail. The final section compares the topologies by addressing the advantages and disadvantages of each electrified topology compared to an aircraft with a conventional gas turbine propulsion. This paper serves as a base for future work on electrified topologies, especially on the fuel cell-based all-electric topology.

2. TOPOLOGIES FOR ELECTRIFIED AIRCRAFT PROPULSION

Based on the source for electric energy, the way it is converted into thrust, and the arrangement of the components, three categories for electric propulsion systems were defined and referenced in [2], [6], [9], [7], [8], [10], [11], [12], [13], [14], [15], [16]. These topologies are divided in all-electric, turbo-electric and hybrid-electric propulsion and are summarized in FIGURE 1.

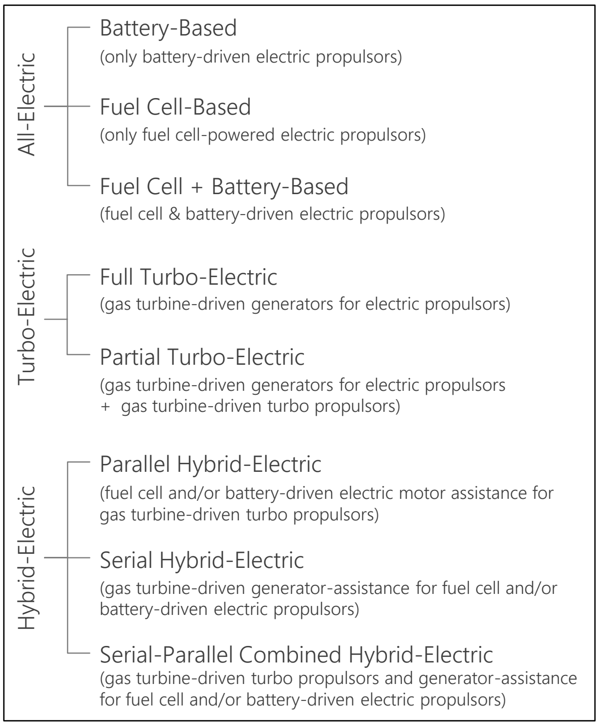

FIGURE 1: Topologies for electric aircraft propulsion.

2.1. All-Electric Aircraft Propulsion

In an all-electric aircraft, no gas turbine is involved, and thrust is usually generated by propulsors driven by electric motors. The electrical energy for the motors is either stored in the batteries, which can be recharged or replaced on the ground (airport) or electrical energy is generated by fuel cells. Other sources such as capacitors and flywheels can also play these roles but not at large scale as they currently deliver low specific energy (15 Wh/kg and 100 Wh/kg respectively) and are not considered in this paper [5], [16]. In all-electric architecture, three different topologies can be defined as shown in FIGURE 2.

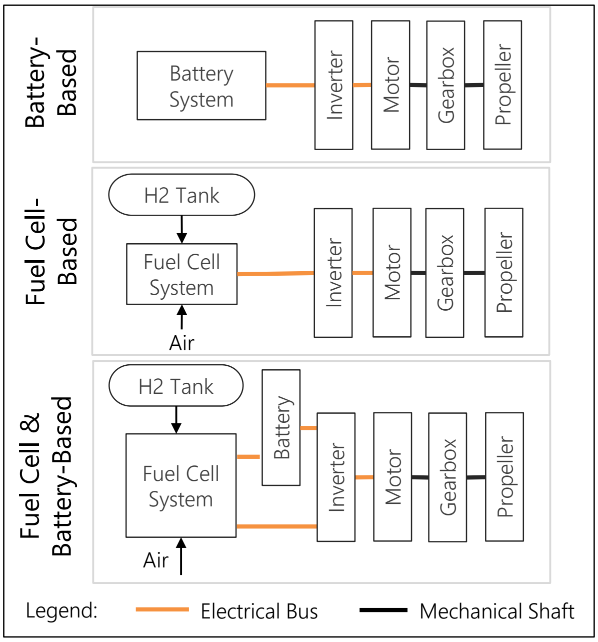

FIGURE 2: Simplified block diagrams for all-electric aircraft propulsion topologies.

2.1.1. Battery-Based All-Electric Propulsion

A battery-based electric propulsion unit generally consists of the sub-systems such as battery system, inverter, power electronics, electric motor, gearbox and propeller, as shown in FIGURE 2. In a battery system, packs of high-performance battery cells serve as energy storage on-board of the aircraft. Those packs require components for their thermal management (cooling and heating of cells for an optimal operating temperature) and structural components to fix and protect the packs against external loads and vibrations. The inverter converts the direct current from the battery into alternating current at a frequency required by the electric motor. The power electronics maintain and distribute the high voltage electric current via cables along the aircraft to the individual electric motors. The electric motor converts the electrical energy into the rotary motion of a shaft. An optional gearbox can regulate the rotational speed between the motor and the propeller. A pitch mechanism is usually built into the propeller assembly for various thrust settings. This paper will not discuss the shaft, gearbox, and propeller, as they are technologically mature and are used in each above-mentioned topology. The largest component in this topology are the battery packs.

A battery pack usually consists of stacked multiple cells. Its performance can be characterized mainly by its mass-specific energy density (also called as gravimetric specific energy), available charge cycles and also fast-charge capability to meet the performance requirements and airport turnaround times. Some estimations for the required battery specifications for different classes of the aircraft are made by Misra in [17], [18]. For short-range small aircraft, NASA estimates the required pack-level battery energy density of 300 Wh/kg for a 30-passenger aircraft and flight range of 483 km. For a regional aircraft with 50 to 70 passengers, 600 Wh/kg specific energy density is required at the cell level. In year 2020, Li-ion pouch cells, with a capacity of 2 Ah and a cell-level specific energy density of 350 Wh/kg, achieved 430 charge cycles with 80% capacity retention [19]. Lithium-sulfur batteries result more promising results with energy density of 471 Wh/kg at the cell level and technology readiness level 4 in 2021 [20]. The energy density at system level is far below the values required for regional aircraft. In general, additional components for the thermal management and packaging of the battery cells increase the overall weight and a reduction of the specific energy density by 30%-40% from the cell level to the pack level [18].

The Ce-Liner aircraft concept envisions a monoplane with battery energy density of 2 kWh/kg for a 1667 km mission with a cruise speed of Mach 0.75 and 189 passengers, which can be expected from year 2035 [3].

2.1.2. Fuel Cell-Based All-Electric Propulsion

In this topology, the electric power (direct current) is generated by the fuel cells on-board of the aircraft using air and fuel such as hydrogen, see FIGURE 2. Fuel cells generate direct current which is converted to alternating current via inverters, which supply electric motors for driving the thrust generating propellers. In general, a fuel cell system is composed of the following subsystems and components [21], [22]:

- Fuel cell stack as a package of single cells, consisting of an electrolyte, e.g. polymer electrolyte membranes (PEM), bipolar plates, seals, and end plates;
- Air management, consisting of compressors/pumps, filters, ducts, valves, collection tanks, water separators, and cathode air recirculation unit;
- Water management (for low temperature, LT-PEM), consisting of pumps, ducts, valves, collection tanks, and components for cathode air separation and humidification unit;
- Thermal management, consisting of heaters, radiators, heat exchangers, coolant, tanks, pumps etc.;
- Fuel management, consisting of fuel (e.g., hydrogen gas for PEM) as anode reactant, reformer (for solid oxide fuel cells, SOFC), pressure valves, tubes, tanks, recirculation and water separation units;
- Power management, consisting of power electronics for current and voltage maintenance (collecting, amplifying, distributing), buffer batteries for auxiliary power, cables, switches and sensors.

The technologies behind fuel cells are well studied and mentioned in references like [18], [23], [24] and are described in Chapter 4.

With regard to the goals of achieving low-carbon emissions, only polymer electrolyte membrane fuel cells (PEMFCs) currently offer a high feasible output of up to 250 kW [25]. With moderate operating temperatures between 60°C - 120°C, PEMFCs allow short start-up times of a few minutes, comparatively long lifetime, no carbon and NO_X emission. They achieve efficiencies between 50% to 68% and a high power density of up to 1 kW/kg [26], [25], [27].

The Antares DLR-H2 of the German Aerospace Center (DLR) in 2009 could take off with a PEMFC system which provided a maximum power of 33 kW during the flight with maximum speed of 170 km/h and an overall aircraft-level efficiency of 50% [28]. General Electric conducted a comparative evaluation between a PEMFC-powered turbofan and a modern gas turbine turbofan with similar fan pressure ratio and net thrust. The topology of the PEMFC-powered turbofan provided benefits in terms of 75% lower specific fuel consumption (SFC), a nearly fourfold reduction in fuel and tank weight, and zero NO_X emissions. On the other hand, SFC improvements with the PEMFC were lower at high power cycles during climb and takeoff. The disadvantages of a fuel cell-based topology were measured in terms of weight and volume of the entire engine. The two fuel cell systems weighed six times more and occupied 4.7 times more volume in the aircraft than two comparable conventional gas turbine-powered turbofan engines [29].

In addition to PEMFCs, SOFCs are also well researched fuel cells, especially in the power generation industry. In general, an SOFC is defined as a high-temperature (600°C - 1000°C) solid-state device of planar or tubular design, consisting of multiple layers of ceramic anodes, electrolytes, and cathodes. The planar design offers higher power densities, simpler design, and less expensive fabrication than the tubular design due to lower losses from a bipolar configuration [30], [31]. Some of the biggest challenges for the application of SOFCs in the aerospace sector are the thermal robustness of the ceramics, as cyclic loads occur during the various phases of flight. This also applies to the cell sealing at high temperatures, which should ideally have similar thermal expansion properties as the adjacent components (more so for planar than for tubular designs). SOFCs are more tolerant of sulfur than PEMFCs, which could damage the chemical process [32]. Currently, SOFC systems have been tested as auxiliary power unit in commercial aircraft and research is going on for its application as propulsion power generation unit [33]. An experimental test on a solely SOFC powered unmanned aerial vehicle demonstrator was found with confidence flight worthy [34].

2.1.3. Fuel Cell and Battery-Based Combined All-Electric Propulsion

This topology, as shown in FIGURE 2, uses a fuel cell system along with a battery system to provide electrical power. Such combination enables the provision of high power and dynamic handling (for transient loads) during takeoff and climb operations by using both systems simultaneously. This architecture also allows the batteries to be recharged using the excess power from the fuel cell system during low-power cruise phase. Power electronics such as cables, power amplifiers and converters are required to condition and transmit the direct current between the battery system and the fuel cell system. An inverter converts this to alternating current, which is then used by a motor to drive a propeller.

A major advantage of this architecture over other all-electric topologies is that the required range and payload capacity for regional aircraft can be achieved by optimizing the size of the fuel tanks, fuel cell system, and high-voltage batteries. Challenges arise in terms of complexity, overall weight, and safety, as both systems require reliable heat, air, water, and power management.

In 2008, Boeing conducted flight tests with a two-seat electric propeller aircraft powered by a PEM fuel cell and Li-ion battery. Takeoff and climb were performed using batteries, and at cruise altitude the pilot was able to fly for 20 minutes at 100 km/h on PEM fuel cells alone [35]. Since 2016, DLR has demonstrated up to 30 takeoffs and flights lasting two hours with the four-seater HY4, an aircraft powered by PEM fuel cells and batteries [36].

2.2. Turbo-Electric Aircraft Propulsion

In general, the topology of a turbo-electric aircraft comprises generators driven by gas turbines supplying electricity to electric motors. The energy is stored on-board of the aircraft in form of conventional or sustainable aviation fuel. As illustrated in FIGURE 3, two main types of this topology can be distinguished. Full turbo-electric, in which only electric motors drive propellers using the power from the generators. Here, the gas turbine's role is only to power the generators, and the shaft power is not used directly to generate thrust.

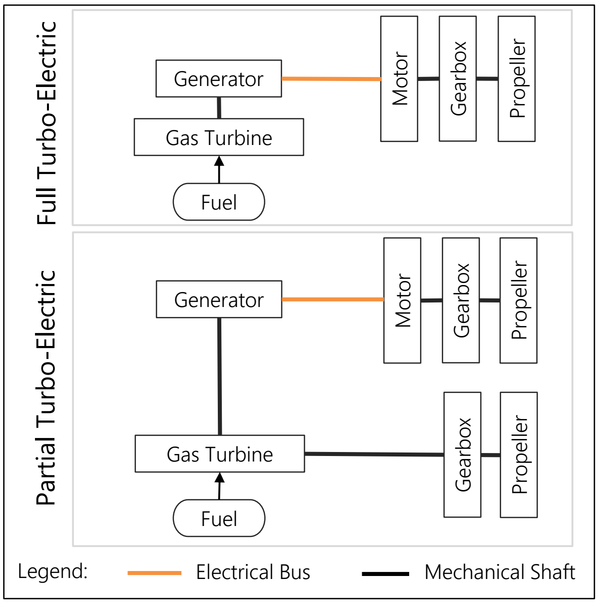

FIGURE 3: Simplified block diagram of turbo-electric topologies.

In the partial turbo-electric topology, an additional propulsor is attached to the gas turbine shaft, and the generator is driven with a portion of the gas turbine's power. Numerous studies have shown the viability of turbo-electric propulsion topologies for achieving the required thrust, range, carrying capacity and turnaround time at the airport for regional aircraft, referenced in following sections.

2.2.1. Full Turbo-Electric Propulsion

In this topology, all electrical power is generated by gas turbine generators. Conventional Jet-A fuel or sustainable SAF can be used as chemical energy source, which do not require major changes in aircraft's tank structure, fuel management and associated operational requirements. The fuel is burned in the combustion chamber of the gas turbine and hot gases are expended in the turbine section, rotating the propeller shaft. Depending on the power output of the gas turbine, several generators with different power outputs can be connected to the shaft. As illustrated in FIGURE 3, multiple electric motors and propellers can be distributed across the aircraft as the power generation unit is decoupled (can be centralized) and the transmission occurs through cables. This offers a number of advantages, such as increased lift, BLI, small propellers, and their independent and flexible operation at optimized speeds. Another advantage of this topology is that the power-generating gas turbines are a highly reliable and mature technology, having a positive impact on the system safety, reliability and certification. Additionally, the required range and payload capacities can be achieved by sizing the fuel tanks for regional to long-range flights. The biggest disadvantages are CO_2 and NO_X emissions, currently associated with the conventional kerosene-based fuel (hydrocarbon fossil fuel). These can also be significantly lowered by replacing it with sustainable aviation fuels or direct combustion of hydrogen in gas turbine, which are currently at low technological levels. NASA's N3-X aircraft was designed as turbo-electric distribution propulsion with multiple electric propulsors powered by two gas turbine core engines for a range of 13890 km, a cruise Mach number of 0.84, and a capacity of 300 passengers. This concept was calculated to have 72% lower fuel consumption compared to similar aircraft with conventional turbo propulsion [1].

2.2.2. Partial Turbo-Electric Propulsion

In this topology, an additional propeller is mounted on the gas turbine shaft for thrust generation, and a portion of the shaft's mechanical energy drives the generators, see FIGURE 3. This topology allows decoupling of the power-generating unit from the thrust-generating unit, providing distributed propulsion and simultaneously, the flexibility to adjust the rate of thrust generation between the turbo unit and the electric unit. For example, during takeoff and climb, the propeller on the turbine shaft can be operated at higher power than the generator, and during cruise, mainly the generator-powered electric motors can be used, which are efficient at low power settings. The challenges associated with this topology are the added complexity and maintenance requirements for turbo propulsion units, and the fact that the development of sustainable fuels and direct combustion of hydrogen are still at a lower technological level than targeted in Flightpath 2050.

The EU-funded CENTRELINE project proposed a partial turbo-electric aircraft for a 12038 km range carrying 340 passengers. Two wing-mounted turbofans were designed to generate 47% of the thrust for the climb phase and to power a 4.6 MW generator with 95% efficiency to drive a tail-mounted electric fan (8 MW motor, pressure ratio 1.4, motor efficiency 95%) [37], [38].

2.3. Hybrid-Electric Aircraft

In general, hybrid-electric propulsion for an aircraft is defined as a combination of gas turbine-driven turbo propulsion unit and battery or fuel cell powered electric propulsion unit. A hybrid-electric aircraft uses different energy sources such as Jet-A fuel with a mass-specific energy of 12000 Wh/kg for high energy requirements during takeoff and a battery and/or fuel cell for low energy requirements during cruise. Hybrid-electric systems have advantages in terms of reducing emissions, especially CO_2 emissions, by using the flexibility of the powertrain in serial, parallel, or mixed configurations. According to Antcliff and Capristan [14], the hybrid-electric powertrain has the most direct path of all hybrid architectures. It offers unique flexibility in power support by utilizing a range of efficiencies between 40% with a turbo drive and 93% with an electric drive. The degree of hybridization between electric and turbo drives is defined as the ratio between the propulsive power generated by the electric drive train and the total propulsive power of the aircraft [39], [40]. It indicates the degree of electrification in a powerplant on a scale from 0 to 1. An optimal degree of hybridization can lead to maximum benefits of hybrid electric aircraft in terms of reduced emissions, low cost and high efficiency, high aircraft reliability (multiple independent engines) and distributed propulsion compared to conventional gas turbine powered aircraft [41]. In Antcliff and Capristan [14], an increase in overall aircraft efficiency was calculated (30%-40% with gas turbine versus 40%-60% with fuel cells and 93% with batteries). More ambitious CO_2 and NO_X reduction can be achieved by replacing the conventional fuel in existing gas turbines with hydrogen gas [42], [43]. This can offer advantages in terms of high power-to-weight ratio and low emission levels. It requires more research and testing for the development of combustion chamber and turbine. Technological challenges include development of hydrogen storage and supply structure, optimization of the injection strategy and the mixture formation patterns in combustion chamber, which can, for example, improve the volumetric efficiency of the engine due to an increased air supply [44], [45].

In the following topologies, the fuel cell unit can be used with a battery pack for charging or without a battery pack for direct power supply to the inverter or in partial combination with a battery pack, as shown in FIGURE 4-6. The pressurized air from the gas turbine's compressor can be used in the PEM fuel cell to meet the reactant demands. Through this no additional pumps or compressors are needed for the fuel cell system. In addition, unused or excess air from the fuel cell system can be recirculated to the gas turbine's flow path to minimize the losses. The need to carry two types of fuel tanks can be eliminated if the hydrogen gas is burned in the gas turbine, which also serves as the reaction fuel for the PEM fuel cells. Such a development is being tested by Airbus as part of the ZEROe project [46].

SOFC applications in hybrid propulsion topologies have potential of a combined thermal management with gas turbine core engine. The unused fuel can be diverted to the combustion chamber, and the exhaust heat can be used to pre-heat the oxidant stream for the SOFC. A feasibility study on SOFC with heavy hydrocarbon fuel identified a specific power of at least 300 W/kg at system level and an efficiency of 60% [47]. The design and performance analysis of a compact SOFC unit coupled to a jet engine showed an increase in specific thrust of 20 to 25% compared to a conventional jet engine with similar requirements. With coupled thermal management between the jet engine exhaust and the fuel reformer for the SOFC, a 6.3% increase in thermal efficiency was calculated [48].

2.3.1. Parallel Hybrid-Electric Propulsion

This topology includes two powertrains that use different energy sources: Fuel (Jet-A or SAF) for the gas turbine and electricity from charged batteries and/or from fuel cell using hydrogen gas. As shown in FIGURE 4, the turbo propulsion unit includes a combustion chamber; a turbine and a compressor connected to a shaft that drives a propeller via an optional gearbox. The electric motor is connected to the same gearbox and clutch unit via a shaft for additional power assistance in parallel. This is needed to adjust the differences between the rotational speed of the shaft from compressor and the shaft from motor. Depending on the mission profile and aircraft architecture, the degree of this power assistance can be regulated in order to achieve optimal fuel consumption and efficiency throughout the flight. As mentioned earlier, the fuel cell unit can be used in conjunction with the battery and/or to directly power the electric motor. If the battery is excluded from this topology, the electric power can be generated by the fuel cell unit using compressed air from compressor and hydrogen gas from a designated tank and the direct current can be bypassed to the inverter as shown in FIGURE 4. In terms of safety and certification, this topology can offer advantages because the propulsion system does not depend solely on the electric motor, but on a more reliable, less failure-prone and higher TRL gas turbine powertrain.

Boeing's SUGAR Volt included two modern turbofan engines, each with a 5500 hp electric motor assistance. During takeoff and climb, both engines jointly generated the required thrust, and during cruise, the turbofans were powered by electric motors, fed by large battery packs with an assumed energy density of 750 Wh/kg for a range of 1667 km. A battery weight of 9480 kg and a wire weight of 454 kg were calculated. The battery packs were mounted under the fuselage and could be replaced at the airport. Advantages resulted in emission reduction, but the main problem was the high total weight of the propulsion system [49].

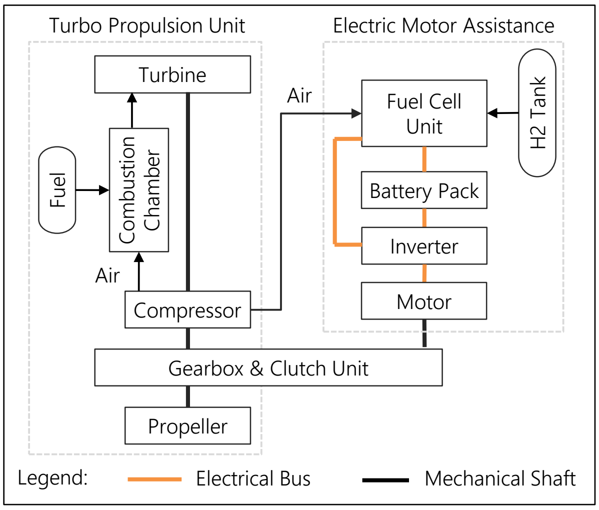

FIGURE 4. Parallel hybrid-electric propulsion topology.

2.3.2. Serial Hybrid-Electric Propulsion

In this topology, the electric power for the motor is supplied either by a gas turbine-powered generator or by a battery pack and/or fuel cell system. The generator driven by the gas turbine provides electric power assistance to the motor, especially during takeoff and climb. A combination of fuel cell unit and battery pack can also be considered for such a topology and would be advantageous if the same fuel is used for combustion in the gas turbine as in the fuel cell, e.g. hydrogen gas (no additional tank structure and fuel management unit). A power distributor is required to condition and convert the incoming electrical currents onto the levels required for the electric motors as per the thrust setting. One advantage is that the gas turbine can be sized smaller and can be operated more efficiently, since no propeller is driven on the shaft [5]. An example for this architecture is shown in the following FIGURE 5.

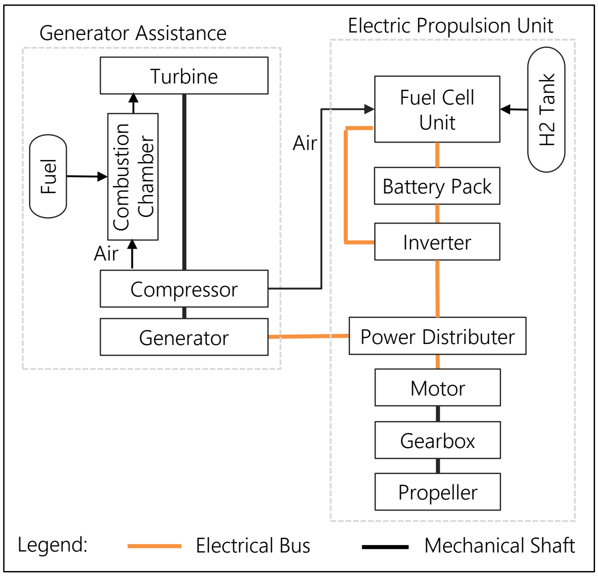

FIGURE 5. Topology for serial hybrid-electric propulsion.

In 2011, the two-seater aircraft HK36 Super Dimona was powered by a 70 kW electric motor, 30 kW of which was generated by a constant-speed generator and the remainder by a battery system [50].

2.3.3. Serial-Parallel Combined Hybrid-Electric Propulsion

Similar to the previous topology, the electric drive unit is supported by a generator, which is connected to the gas turbine. In addition, propellers are also connected to the gas turbine shaft via the gearbox, see FIGURE 6. This provides a high degree of flexibility in thrust generation.

A feasible example is NASA's PEGASUS [14], [51] with a capacity of 48 passengers and a range of 370 km. Two electric motored propellers were mounted on the tip of the wings and were designed to be foldable for the cruise phase. It resulted in an 18% increase in effective propulsion efficiency [14]. They also provided additional propulsion support during takeoff and climb. In addition, a battery-powered electric propeller was placed at the tail for the BLI to increase overall efficiency. In PEGASUS, a specific energy density for the battery of 500 Wh/kg was assumed, which is currently not achievable and represents the greatest challenge for this topology. Another example is the SUSAN concept featuring a hybrid electric propulsion system with a combination of a tail-mounted turbofan (35% thrust) simultaneously driving four 5-MW generators, producing a total of 20 MW of power for 16 counter-rotating electric fans (65% thrust) mounted on the wings. Backup batteries were installed for emergency operation. Capacity was set for 180 passengers and a mission length of 4630 km [52], [53], [54].

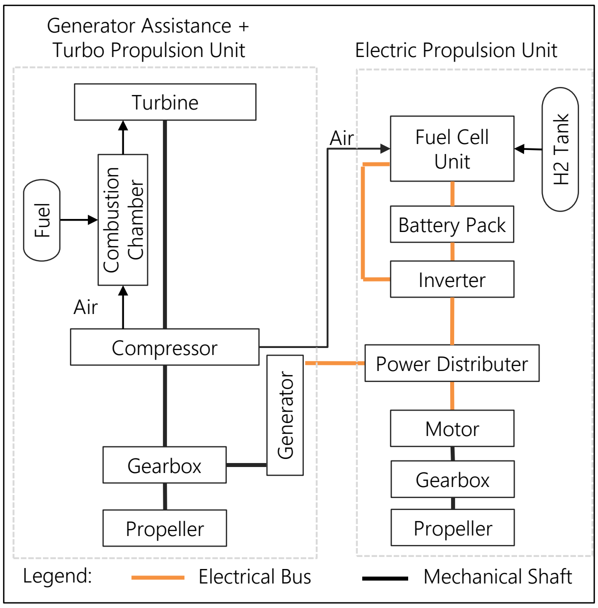

FIGURE 6. Topology for serial-parallel combined hybrid-electric propulsion.

3. CHALLENGES FOR CRITICAL COMPONENTS

In general, the challenges for electric propulsion can be categorized in systemic, technical, economic and policy challenges [9], [47].

Systemic challenges are about making an aircraft technology competitive by offering low-emission (CO_2, NO_X and noise), low-cost and less complex solutions. A direct influence on CO_2 emissions is made by the fuel as a critical component. The challenge of reducing costs is crucial for the components, which require research, development and testing. This applies for high-performance batteries and fuel cell systems as well as to the gas turbine with direct combustion of H_2 and the development of SAF. The challenge of reducing complexity at the aircraft level requires a high standard of systems engineering to integrate new components into the existing aircraft structure. This is also a critical challenge for the components in topologies that do not use a reliable gas turbine and need to increase technological readiness level [9].

The technical challenges can be associated with improvement of thermal and propulsive efficiency of the system, as well as with manufacturing lightweight and small-sized components. Basically, propulsive efficiency defines the effectiveness of energy conversion from fuel or electricity into thrust on-board of an aircraft. High efficiency means low fuel or power consumption to complete a flight mission. The thermal efficiency of a system can be increased by maintaining operating temperatures and limiting heat losses across the system boundaries and/or by coupling the heat source and heat sink within the system. Another technical challenge for the components is to minimize their weight and decrease their size. Through this, the energy density of a battery system and fuel cell system can be increased. Additionally, multiple components can be utilized in limited design space for high redundancy (less dependencies on other components) and reliability.

Economic challenges result from the development of the supply chain, raw materials, and the infrastructure for SAF and hydrogen fuel. These are affected due to global economic uncertainties, particularly with respect to net fuel prices and fluctuations due to natural disasters, pandemics, or disrupted supply chains.

Policy challenges include the development of regulations and standards for the evaluation and certification of new components, such as high-performance batteries, power electronics, and fuel cell systems. These also apply to the modification in aircraft design for allowing BLI, distributed propulsion, cryogenic cooled system and fuel tanks. These challenges are addressed in the following chapter for selected components.

4. CRITICAL COMPONENTS FOR ELECTRIFIED AIRCRAFT PROPULSION

This chapter describes the main components mentioned in the previous chapter. It covers their description, functions, current technological developments and the challenges against their feasibility in electric propulsion.

4.1. Battery System

A battery pack is a group of individual battery cells stacked and connected together to store electric charges (energy). A battery cell is typically composed of anode and cathode electrodes. Four main types of cells are discussed in the section below. Power electronics for a battery system contains connectors, switches, sensors, cables and breakers for the transmission, control and monitor of the electric charge to and from the battery packs (charging - discharging). The components for the thermal management of a battery system are coolant, heat exchangers, radiators, pumps and valves, which regulate the heat flow in the system and maintain the required temperatures in and around the battery packs. In order to secure the battery packs and sub-components against external loads and vibration, structural components such as stiffeners and fixtures are used.

Few well-known types of battery cells which have potential for application in regional aircraft, are lithium-ion (Li-ion), lithium-metal (Li-metal), lithium-sulfur (Li-S) and lithium-air (Li-air) batteries. Recent developments in battery cell technology can be characterized as improvement of the lithium-ion battery with graphite anode and transition metal oxide cathode, fast charging capability, low temperature performance, and improved tolerances against external conditions. According to the U.S. Department of Energy, the next generation of lithium-ion batteries is capable of increasing specific energy density by using silicon alloy anodes (potential 400 Wh/kg at the cell level) and lithium metal anodes (> 400 Wh/kg at the cell level) [18], [19]. With such developments, the required specific energy density at battery cell level of 300 Wh/kg can be achieved for a short-range application with 30 passengers. The technical challenge remains for higher demands of 600 Wh/kg for regional aircraft with 50 to 70 passengers [17], [18]. This value drops by 30% to 40% from cell level to pack (system) level.

Recent developments indicate that Li-metal batteries have the potential to achieve a specific energy density of over 300 Wh/kg at the cell level [55]. In 2021, an anode-free Li-metal battery with a capacity of 300 mAh and a cell-level specific energy density of 350 Wh/kg (including the aluminum foil packaging) achieved 100 cycles with 84% capacity retention. A copper foil was used together with lithium as the electrode to reduce ion losses and increase lithium utilization [56]. In December 2020, a Li-metal pouch cell with ion-selective nanofluid transport in a conjugated microporous polymer layer was tested with a capacity of 8.15 Ah and an energy density of 400 Wh/kg, but a much too low cycling stability of 65 cycles [57]. In 2020, Li-ion battery cells with improved Li-metal were tested with 2 Ah capacity and a specific energy density of 350 Wh/kg achieved 430 cycles with 80% capacity retention [19]. In addition to specific energy density, rapid battery charging capability is required for short turnaround times at airports. Microvast's Li-ion 35 Ah pouch cells demonstrated over 1000 charge cycles with a 10-minute fast charge using advanced components for the cathode [19] and separator technology with high thermal stability studied in [58].

Another mature battery technology is the lithium-sulfur (Li-S) battery, where the metallic cathode of the Li-ion cell is replaced by a sulfur element. Compared to Li-ion metal batteries, Li-S batteries offer a cost-effective solution with higher gravimetric energy density (theoretical 2700 Wh/kg) due to their lightweight cells [59]. The main disadvantage is the short lifetime of Li-S batteries compared to Li-ion metal technology. The state of the art for Li-S batteries tested by OXIS Energy in 2020 was an energy density of 471 Wh/kg at cell level, with a target of 600 Wh/kg in 2025 [20]. A Li-air battery offers higher energy density than current Li-ion battery technology and can have up to 750 charging and discharging cycles [60]. In Japan, an energy density of over 500 Wh/kg was tested at room temperature [61].

One feature of the battery system is its modularity. Several battery packs can be connected to form modules that can be integrated into the aircraft. Heat is generated during the use of a high-voltage battery system in aircraft. The heat generated by a Li-ion battery depends on the charging and discharging rates, the state of charge and the temperatures [62]. On the contrary, heating is necessary during the cold ambient conditions for the battery system to be operational [63]. This requires a thermal management system, which must be developed in similar modulations to that of the battery packs. Thermal management for the battery module can include several methods. The most common are the combination of coolant and air through the module boundaries and active or passive cooling at the bottom and side walls of the battery packs. CO_2 gas is preferred for battery air conditioning because it is inert to battery chemistry and non-flammable [63]. The safety of the batteries can be defined as the chemical safety of the cell material and separators; the electrical safety including the insulations for the housing, cables, etc.; the mechanical safety of the entire battery module including the vibration and shock resistant housing; the robustness of the thermal management (venting); and the functional safety of the sensors, control unit, relays and electrical buses [63]. The efficiency of a battery is usually defined as the ratio between the energy released during discharging and the energy stored during charging. Li-ion batteries have a high efficiency of over 95% [63]. Technical challenges arise from the prevention of ion-losses in the cells; degradation at low ambient temperatures; decreasing retention after increasing cycles (decreasing charge capacity with time and charge-discharge cycles); as well as fire and overheating risk in high-voltage applications. Another requirement for the battery system can be to oversize its capacity to power the accessory systems, such as moving flaps and slats that are conventionally driven by hydraulics powered by the gas turbine. In addition, there are technical challenges related to lightweight design of non-cell mass such as fairings, fasteners, fireproof envelopes, and the battery cooling system.

Some systemic challenges of reducing the emissions can be solved if the electricity for battery charging is generated through renewable energy sources such as solar wind, hydro and nuclear, rather than conventional coal-fired power plants. The challenges regarding the complexity of integrating the battery system in an aircraft are discussed in followings. When the battery packs are retrofitted into the wings, where the conventional fuel tanks are located, there are design challenges related to maintaining the aircraft's center of gravity balanced until the end of the flight; balancing the flexing of the wings; and supporting the battery mass, including the mass of the subcomponents. If the battery packs are placed in the payload bay inside aircraft, additional thermal management is required to dissipate heat from the airframe, making the overall system heavier and more complex. Additional fire zones and ventilation systems are also required. The demanded large volume and overall weight of the battery system reduce the required carrying capacity of the aircraft.

The policy challenges for battery systems can be defined in terms of safety and certification issues related to the operation of high-voltage batteries and modifications in aircraft to integrate the battery system in airframe.

4.2. Fuel and Storage

In aircraft, different fuel types can be used to store the energy for the operation of thrust and electric power generation. Apart from the conventional kerosene-based jet fuel, sustainable aviation fuel (SAF) and H_2 can be used in aircraft yielding more promising results in terms of CO_2 and NO_X reduction.

SAFs have the potential to be CO_2 neutral and produce fewer contrails than conventional kerosene-based jet fuel, resulting in up to 1.7 times less cumulative global emissions [64]. SAF are "drop-in" fuels that can use the conventional combustion technology in a gas turbine, resulting in the same NO_X emissions as kerosene-based fuel. The key challenge for the use of SAF in regional aviation is the carbon-neutral and economical production in large quantities. For storage, the existing tank structure in aircraft can be used, which is very reliable and at a high technological level.

Hydrogen offers enormous potential for achieving the environmental goals of the Flightpath 2050, especially with the fuel cell as a power generation unit. Alternatively, hydrogen can be used as fuel for direct combustion in a gas turbine. The use of H_2 poses policy challenges in terms of safety, as hydrogen is more flammable than natural gas or kerosene. Complex and reliable sealing and detection technologies are required to prevent and detect hydrogen gas leakage [65]. Another challenge is the ability of hydrogen to diffuse into solid materials, known as hydrogen embrittlement, which damages or reduces the structural strength of metals or alloys in contact. In a combustion chamber, keeping the flame accurate and at a sufficient distance from the metal walls causes technical challenges and requires costly research and development. Direct combustion of hydrogen in a gas turbine was tested in a stationary gas turbine with 30% hydrogen and 70% natural gas, resulting in 10% less CO_2 emissions compared to a purely natural gas-powered gas turbine [66].

Hydrogen storage still presents systemic challenges in the aviation sector, as it increases complexity and weight of the whole system. Due to the low density of hydrogen gas (0.089 kg/m^3 at sea level), large storage space is required in the aircraft. Hydrogen gas is 2.8 times lighter but 4 times larger in volume than kerosene at same energy level. The empty tanks need to be pressurized, which adds complexity and power demand [67]. It can be stored in pressurized tanks in gaseous or liquid form. The associated technical challenge for such storage is that fuel filling must occur at very high pressure and volumetric density. In addition, there are losses due to evaporation and leakage of hydrogen in the tanks and pipelines. Storing hydrogen in liquid cryogenic form (-260 °C) requires refrigeration technology, robust insulation, on-site fabrication to reduce losses during transport, pressurization techniques to maintain the thermodynamic state, as well as additional purge gas to seal the tanks and piping [68], [69]. Another option for storing hydrogen is chemical storage in the form of metal hydrides, carbon nanotubes or glass microspheres. A general disadvantage of chemical hydrogen storages is the weight of the carrier substances once the hydrogen is separated, which is carried during the whole flight.

4.3. Fuel Cell System

A fuel cell system can be defined as an arrangement of fuel cell stacks together with subcomponents for fuel and air supply units (fuel, pumps, compressor, filters, valves, sensors, etc.), water and thermal management (heat exchangers, pipes, coolant, tanks, pumps, valves, etc.), and control & power system (control unit, cables, interconnectors, etc.). Following FIGURE 7 illustrates the LT-PEM fuel cell system and interactions between its subsystems.

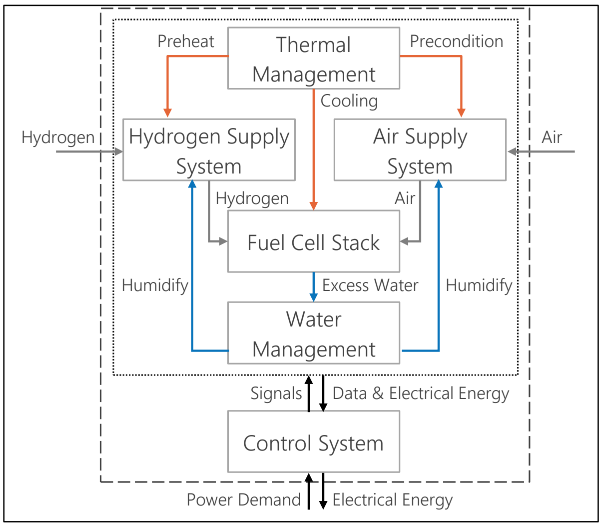

FIGURE 7: Example of a LT-PEM fuel cell system © Kazula, Graff et al. [70, p. 2615]

There are several types of fuel cells such as LT-PEM and HT-PEM, alkaline fuel cells, direct methanol fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and SOFC which differ in their type of electrolytes, reactants, reaction temperatures and design. Their operating principles and characteristics are not covered in this paper and can be found in literature [18], [23], [24]. These references demonstrate that the PEMFC and SOFC offer high efficiencies with mature technologies for their applications in short to medium range electric aircraft. This paper focuses on the LT-PEM fuel cell system, whose main components are described as follows.

A PEM fuel cell requires a homogeneous distribution and balanced transportation of the reactants, heat, water and electric current across the system. Current density distribution and mass transfer in the fuel cell can be improved by new electrode structures such as 3D catalyst layers with carbon aggregate and the use of platinum in the cathode and ionomer adhesion form [71]. Dispersed platinum nanoparticles with optimal carbon size (narrow distance between support and electrode layer) can enhance oxygen reduction activity with ultra-thin metal loading. The selective absorption of platinum particles on carbon enables strong interaction, with 65% of activity retained after 30000 cycles at 60°C, and has the potential for a compact and lightweight PEM stack [72]. Improvement in performance and water transport characteristics can be achieved by using ejectors in primary flow channels (increasing pressure) and secondary flow channels (optimizing relative humidity). The power density can be increased by 37.8% and 86.5% when the primary flow pressure of the ejectors is 300 and 400 kPa, respectively [73], [74]. Improving the durability of PEMFCs without sacrificing performance can increase their potential for commercialization. The addition of Nafion and epoxy as a binder, doped with graphene nanoplatelets, improves the fuel cell performance and increases the mechanical stability of the electrodes, avoiding the loss of catalyst during electrode manipulation during assembly and increasing the durability of the fuel cell [75].

A thermal management is required to control the operating temperature of the cells, preheat the reactants and remove excess heat, generated during the electrochemical reaction between hydrogen and air from individual cells. About 30-70% of the chemical energy is converted into heat [76]. The major components of a thermal management system include the coolant, heat exchangers, radiators, and pumps. Depending on the heat transfer rates between the sources and sinks, different thermal cycles can be implemented, such as air-to-air, liquid-to-air, or liquid-to-liquid heat transfer. The choice of coolant can be made between air, water, ethanol-water mixture, fuel (kerosene or cryogenic liquids such as hydrogen, helium or nitrogen), lubricating oils, and nanofluids. The coolant must have a high thermal conductivity and a high heat transfer coefficient, and at the same time have a low power consumption for the pumps and a freezing point as low as possible to enable cold start of the PEMFC. Nanofluids as coolants offer better results in the above-mentioned properties compared to conventional coolants [76], [77]. The electrical conductivity of the coolant presents challenges in terms of an additional deionization unit and the associated structural weight. Possible heat sinks include the cold leading edges of the wings, nacelle lips, cold intake air that needs to be heated, for example, for cabin pressure and on-board applications, etc. The thermal management system must be designed with redundancy to handle failures or extreme scenarios.

An example is restarting of the fuel cell unit during flight, where preheating of the reactants must be independent of the heat source of the fuel cell itself. In such cases, other heat sources such as the electric motor, transmission, and power electronics can be used to condition the fuel cell stacks and preheat the reactants. The efficiency of the thermal management system increases when the amount of heat dissipated is reduced and the majority of the thermal energy is used within the propulsion unit [78]. The challenges with the thermal management system occur due to high complexity; high required reliability and redundancy; large size (heat exchanger, cooler); heavy weight (coolant, pipes, pumps); and high energy consumption (e.g. coolant transport over long distances through the aircraft fuselage). Many of these aspects are relatively new with unknown effects at aircraft level and require cost intensive research and tests.

Air management for the fuel cell system includes components such as air compressors, air ducts, filters, flow dividers, air intake etc. The compressors can be single or multi-stage, axial and/or centrifugal. The size of the compressor depends on various requirements. A large compressor is needed if, in addition to the cathode flow, air is used as a coolant for the fuel cell stacks; for water removal from the cells; for the anti-icing system at the leading edge of the wing (hot air blow-off) and the nacelle lips; for pressurization of the cabin; and for the fire protection and extinguishing system [79]. Another critical challenge for the air system is to provide the required and constant amount of cathode air for the fuel cells, which can be challenging during the flight at higher altitudes. The air management system can be optimized in size if the hot exhaust from fuel cell stacks can be used to preheat the reactants and/or for ventilating the fire zones [78], [80].

Water management is required for LT-PEM fuel cells, where operating temperatures remain below the boiling point of water and no vapors are generated. This subsystem requires pumps, pipes, water separators, deionization units (if water is reused or returned to the fuel cells in the form of coolant) etc. Similar to air management, water can be reused to humidify cathode air, to transfer heat from the fuel cell stacks into heat sinks such as spraying radiators (increased heat transfer capacity) and as hot water for on-board use. The water from the fuel cell exhaust is rich in enthalpy and the overall efficiency of the propulsion system can be increased by reusing it in aircraft before being purged into the environment [24], [78].

The fuel management unit supplies the hydrogen gas to the fuel cell stacks from the tanks. The main components include hydrogen tanks, pipes, pressure valves (to throttle the fuel gas from high to low pressure), valves to regulate the mass flow rate, thermal management to preheat the fuel, collection tanks, recirculation loop (pump, pipes, manifolds, valves), water separator, deionization unit, and purge valves. Some challenges related to fuel management are as follows. To increase the efficiency of the fuel cell system, recirculation of the hydrogen gas is highly recommended. This requires additional hardware such as pumps, water separators, mixture tanks, sensors, etc., and involves some complexity and safety risks (due to possible leakage). The hydrogen purge gas must be diluted with a nonflammable medium such as water before purging. The hydrogen gas must be purged from the fuel cell stacks at regular intervals to maintain a constant integral of stack load, limited by an ampere threshold of the stack [78].

Compared to a conventional kerosene-based gas turbine engine, a fuel cell-based propulsion system weighs more than twice, resulting in a reduction in payload capacity for the same thrust performance [81]. Oversizing the fuel cell system is a systemic challenge (increasing complexity and integration issues) as power multiplication increases average efficiency, it also increases system mass, which reduces the achievable flight range per kWh from the fuel cell propulsion system [24]. Fuel cell efficiency degrades over time and under varying loads. A long-term study (180 days of continuous operation) with PEMFC showed a 7.2% drop in efficiency when the operating voltage was varied, and up to 14.7% when the fuel cell temperature was not controlled and remained at 95°C [82]. In terms of manufacturing, optimizations in electrode design and new materials (Nafion, graphene nanoplatelets, etc.) are needed to balance gas transport, electrical conductivity, proton transport, and water balance. Performance of the electro-chemical reaction in PEM can be enhanced by reducing the resistance in the cathode-oxygen reaction [71].

A SOFC system cascaded with thermionic and thermoelectric generators and fueled with hydrogen gas for a small unmanned aerial vehicle provided 481.3W of propulsion power with an overall efficiency of 46.7% [83]. A high-power density SOFC, developed by NASA Glenn Center is able to deliver 2.5kW/kg of power density with a volumetric power density of 7.5kW/L. It presents novel technology of bi-electrode supported cell, operating on hydrogen and hydrocarbon-based fuels without reformers [84]. Development in SOFC technology is done for its cathode structure including microstructural modifications by composite, doping, infiltration technique and synthesis method. The introduction of an electrolyte layer-free fuel cell using natural resources and a cost-reducing variant was investigated by Ahmad et al. [85]. The search for a suitable material for the SOFC cathode with high electrocatalytic properties at an operating temperature of 400°C-800°C remains a technical challenge. This also applies to the lightweight solution for the desulfurization unit for SOFC fuel treatment.

Policy challenges with respect to the reliability and safety of fuel cell systems remain critical and require cost intensive research and development. These include power-up procedures, its electrical conductivity, the reactivity of fuel cells after long hours of operation, cold start below -30°C, and their dynamic and variable charging behavior.

4.4. Power Transmission Components

Power transmission between the electricity source and the consumers is carried out with the help of power electronics, inverters, cables, switchgear, circuit breakers, etc. The cables are one of the most important components among them. DC cables are used to transmit the direct-current between the battery packs or fuel cell unit and the inverters (generally) in order to convert it in alternate-current. AC cables are used between the inverters and the electric motors to transfer the alternating current between them. The motor converts the electrical energy into the rotary motion of a shaft. The mechanical shaft transmits power from the motor to the propeller through an optional gearbox. The location of these components and the size of the cables depend on the type of the topology; its location in the aircraft; redundancy plans; power requirements for different phases of flight; etc. For example, if the battery pack or fuel cell unit is housed centrally (in the fuselage) together with the inverters, the length of the DC cables can be reduced. On the other hand, this increases the length of the AC transmission cables to the electric motors. If the inverters are placed near the motors, longer DC cables are required. Both types of cables have different characteristics such as transmission rate, weight and losses in form of resistance and heat generation. To achieve high efficiency at the aircraft level, trade-offs must be made, such as between power transmission, cooling requirements, and weight of the entire system. In a distributed propulsion topology, multiple small battery packs can be located near the inverters and propulsion units, reducing cable length, weight, associated losses, and cooling requirements. An overview of distributed drive technology with several examples can be found in Sahoo et al. [5] and a comparative evaluation of the architecture of AC and DC systems is provided Sadey et al. [86]. The Netherlands Aerospace Center has studied the weight reduction of cables in aircraft engines in the form of flat cables. The derating of flat cables is related to the number of layers. In tests, a single-layer flat cable showed increased current carrying capacity, which could lead to a weight reduction of up to 60% compared to the conventional technology [87].

Due to the absence of a gas turbine and thus a high-pressure medium, the hydraulic or pneumatic components in electric propulsion topologies are generally replaced by electrical components, requiring additional inverters and power electronics. An inverter uses passive filters to balance the output voltage and reduce electromagnetic noise caused by common-mode voltages [88]. With more electrical applications in all-electric drive topologies, the weight and complexity of inverter units can become an issue. Research is being conducted in this area, such as the gradient-controlled voltage inverters by Mitsubishi Electric Corporation [88].

4.5. Motor

In terms of motor selection, the trend is going toward high-temperature superconducting electric motors with cryogenic cooling that can achieve high mass-specific power density and efficiency. NASA has established a schedule of engine performance for various classes of aircraft from 2015 to 2035 [13]. For aircraft capacities of 19-, 50-, 150- and 300-seaters, total electrical power requirements of 2 MW, 3 MW (propeller), 22 MW and 60 MW, respectively, were calculated. To meet these demands, several electric motors with high power and efficient thermal management would be required. In general, the motor for an electric aircraft is characterized by total power, efficiency, and mass-specific energy density. The design of such motors is evaluated in terms of their power sensitivity to the maximum continuous current in the stator and rotor, and the existing air gap between them. An example of a high-efficiency megawatt motor comes from NASA Glenn Research Center, which offers a motor with 1.4 MW power, 98% efficiency, cryogenic cooling, and a specific power density relative to electromagnetic mass of 16 kW/kg [89]. Overviews on some existing motor technology for the aviation sector are made by Sahoo et al. [5] and Hepperle [16]. As part of NASA's Convergent Aeronautics Solutions project, a novel rim-drive motor has been developed in conjunction with an aqueous fast-charge battery (Nano-electric fuel), estimated specific energy density of 2 kW/kg for a full-scale model [90]. The rim-driven motor is designed with a rotating structure on the outer diameter that produces torque with higher efficiency than a conventional hub-mounted rotor by enabling higher rotor tip speeds.

One of the technical challenges for the motor and generator is their cooling to reduce thermal losses. As the trend goes towards large and powerful motors with permanent magnets; reliable and large-scale thermal management is required to reduce the losses. Cryogenic cooling is currently being explored to achieve these goals and to enable the use of high-performance motors.

5. CONCLUSION

A quantitative comparison between the different topologies is difficult at this stage, as this would require a common definition of the aircraft, thrust and mission requirements, and design flexibility for component integration. Reliable and realistic implementation of electric propulsion topologies must overcome the systemic, technical, economic and policy challenges, mentioned in above chapters. It should provide advantages over conventional gas turbine-based turbo propulsion technology, which is already optimized to its limits in terms of low weight, low volume, high reliability, high efficiency, and low cost [9], [40].

Few key advantages of the above-mentioned topologies relative to conventional gas turbine propulsion with Jet-A fuel can be summarized as follows.

All-electric propulsion with battery and fuel cell system:

- Low CO_2 emission if production of H_2 and electricity for battery charging is done using renewable sources;
- No NO_X emission, as no high-temperature combustion occurs in battery and fuel cell systems;
- High efficiency at low power phase (cruise) and great potential of SFC reduction relative to turbo propulsion at same thrust generation;
- High-torque electric motor enables low-speed aircraft operation and takeoffs at short runway;
- De-coupling of energy generation and thrust generation units enabling distributed propulsion, BLI, small propeller and low-drag laminar wing;
- Less noise and quick start during taxing and takeoff through electric motor propulsion [5], [91], [92].

Turbo-electric propulsion with gas turbine:

- Low CO_2 emission with carbon-free SAF or direct combustion of H_2;
- High efficiencies with small-sized gas turbine for generator operation;
- Low SFC and operational flexibility due to de-coupling of energy generation and thrust generation units (and duel thrust production unit in partial-turbo electric topology) enabling distributed propulsion, BLI, small propeller and low drag laminar wing;
- Low cost for development and low technical challenges as most components exist with high TRL;
- Less systemic challenges for components integration if conventional fuel or SAF used;
- Low policy challenges due to high reliability with existing technologies for generator, gas turbine and associated air and thermal management and rules for operation, maintenance and certification.

Hybrid-electric topology with electric and turbo propulsion units:

- Low CO_2 emission by using H_2 as fuel partially, or fully (direct combustion in gas turbine);
- High propulsive efficiency through motorized (low rpm speed) assistance for propeller and flexible power ratio between battery and generator for electric motor;
- Low SFC possible by using flexible degree of hybridization (low-power flight through more fuel cell operation and high-power flight through more turbo propulsion) and optimized gas generator operation with BLI, distributed propulsion and foldable propellers;
- Less noise and quick start during taxing and takeoff due to electric motor assistance [5], [91], [92];
- Low policy challenges due to utilization of gas turbine thrust unit with high reliability and existing operational, maintenance and certification rules;
- Less complex due to existence of gas turbine as no oversized electric motor required for one-motor failure scenario and existing secondary air, thermal, hydraulic and pneumatic systems can be utilized;
- High efficiency due to no power offtakes on gas turbine shaft;
- Less complex in terms of fuel cell system integration as coupled heat management between gas turbine and fuel cell unit is possible, utilizing compressed hot air for cold-start assistance for fuel cells, heat for fuel reformer (SOFC) and airflow for heat exchangers;
- Less complex as mechanical coupling between the powertrains enables recharging of batteries at low-power flight phase in which the electric motor acts as an electric generator, reducing the size of the battery pack relative to non-charging option and reducing penalties due to dead-weight of batteries;

The major challenges for the electric propulsion topologies are summarized as follows.

Challenges for all-electric topologies with battery and fuel cell system are:

- To integrate the battery system, fuel cell system and H_2 tanks in existing aircrafts and approvals requirement for safety and certification;
- To reduce the cost for research and development of high energy density battery and fuel cell systems together with the production, transportation and storage of H_2;
- To develop lightweight design for the components of fuel cell and battery systems especially air and thermal management units including leakage management and fuel reforming (SOFC);
- To achieve the regulatory and safety approvals for cold condition start (PEMFC), power losses at low temperatures (Battery), fire at high temperature (power electronics), insufficient dynamic behavior (PEMFC) and for functions such as thrust generation and hydraulics in absence of gas turbine's reliability;
- To improve the efficiency (especially fuel cell) for high power requirements during takeoff and climb and to reduce penalties for carrying dead-battery mass;
- To increase resistance against thermomechanical fatigue loads, especially for SOFCs.

Challenges with turbo-electric topologies with involvement of gas turbine and electric motor can be:

- To achieve low levels of CO_2, NO_X emission with conventional kerosene-based fuels;
- To reduce the cost for the production and sustainable supply-chain of carbon-free SAF and H_2 together with research and development cost for the direct combustion of H_2 in gas turbine;
- To reduce noise emissions during takeoff and taxing caused by gas turbine operation for electric power generation;
- To achieve regulatory and safety approvals for electric propulsion unit (full turbo-electric), also linked to oversizing the electric motor for one-engine-inoperability case;
- To reduce complexity between gas turbine-based power generation and electric propulsion unit in coupling, integration and thermal management.

Key challenges with hybrid-electric topology with the involvement of gas turbine can be:

- To reduce noise emissions during takeoff and taxing cause by gas turbine operation for electric power generation;
- To improve global efficiency with lightweight design of electric components, battery and fuel cell systems and also to compensate for dead-battery mass penalties;
- To reduce complexity linked to the integration of duel propulsion units such as separate fuel management (if no H_2 combustion in gas turbine occurs), limited size of fuel tanks, mechanical coupling between motor and gas turbine shaft (parallel hybrid-electric), electrical coupling with increased cooling requirements (serial hybrid-electric) and heat management unit for each fuel cell, battery and gas turbine system;

- To reduce the safety and certification issues due to low TRL of motor-driven propulsion, increased failure chances for hydraulic and secondary air applications (due to reduced compressor operation at low rpm in parallel hybrid-electric).

This paper serves as research on existing technologies, challenges and for identification of critical components in various possible electric propulsion topologies. The global goals of achieving reduced emission levels, flight range and payload capacity with required safety and redundancy can be realized with all-electric topologies mostly through increasing energy density of the fuel cell and battery system. This is also true for the novel design for airframe to integrate hydrogen tanks. This can be done via lightweight design of the components especially for thermal and air management; drag reducing technologies such as BLI, distributed propulsion and laminar wings; application of super-conducting and cryogenic cooled electric components; and through small-sized multiple redundant systems integrated systemically in airframe. These aspects also apply for hybrid-electric topologies with the additional challenge of reducing complexity and weight of the whole propulsion system due to the existence of duel powertrains and energy storages. The most critical component for turbo-electric topologies to achieve emission goals can be the development of SAF with carbon-free or low-carbon emission for its production and/or technology for direction combustion of H_2 in existing gas turbine powertrain. This paper serves as a base for future work on electrified topologies, especially on the fuel cell-based all-electric topology for short-haul regional aircraft with a carrying capacity of more than 19 passengers

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