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Implementation of Fuel Cells in Aviation from a Maintenance, Repair and Overhaul Perspective

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Abstract: Hydrogen is one of the most promising power sources for meeting the aviation sector's long-term decarbonization goals. Although on-board hydrogen systems, namely, fuel cells, are extensively researched, the maintenance, repair and overhaul (MRO) perspective remains mostly unaddressed. This paper analyzes fuel cells from an MRO standpoint, based on a literature review and comparison with the automotive sector. It also examines how well the business models and key resources of MRO providers are currently suited to provide future MRO services. It is shown that fuel cells require extensive MRO activities and that these are needed to meet the aviation sector's requirements for price, safety and, especially, durability. To some extent, experience from the automotive sector can be built upon, particularly with respect to facility requirements and qualification of personnel. Yet, MRO providers' existing resources only partially allow them to provide these services. MRO providers' underlying business models must adapt to the implementation of fuel cells in the aviation sector. MRO providers and services should, therefore, be considered and act as enablers for the introduction of fuel cells in the aviation industry.

Keywords: aviation; liquid-hydrogen-fueled aircraft; fuel cell; maintenance; business model analysis

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1. Introduction

To contribute to the global effort to reduce greenhouse gases, the aviation industry has to meet increasingly strict externally and internally imposed decarbonization goals. While, in 2009, a commitment from the International Air Transport Association called for a 50% reduction in emissions by 2050 and carbon-neutral growth from 2020 onward [1], the goal now is to achieve net-zero carbon emissions by 2050 [2]. The former is also the official position of the International Civil Aviation Organization [3]. The European Union is calling for a 90% emissions reduction by 2050 in the whole transportation sector, including aviation, as part of the New Green Deal [4], and refocusing the goal to reduce carbon dioxide CO_2 emissions by 75% by 2050 set in 2011 [5]. Even though these targets have different timelines and exact values, it is clear that the aviation sector faces a challenging decarbonization process. To manage this process successfully, a wide range of technologies must be further developed and implemented. One of the most promising technologies is the use of liquid hydrogen (LH2) as an energy source inside the aircraft [6]. This has also been recognized by the aviation industry, such as the major aircraft manufacturer Airbus, with its ambitious goal to develop a short-to-medium range hydrogen-powered aircraft by 2035, called ZEROe [7]. An overview of past and ongoing projects relating to hydrogen-powered aircraft is given in Table 1.

Table 1. Excerpt from relevant projects on hydrogen-powered aircraft.

Year	Project Name	Base Aircraft	Typ of Hydrogen Usage	Institution	Source
1957	Bee	Martin B-57B	Direct combustion	NASA	[8]
1988	Tu-155	Tu-154	Direct combustion	Tupolev	[8]
2008	-	Diamond DA20	polymer electrolyte membrane fuel cell (PEMFC)	Boeing	[9,10]
2008	ELBASYS	A320	PEMFC as auxiliary power unit (APU)	DLR	[11]
2009	Antares	Antares 20E	PEMFC	DLR	[12]
2010	ENFICA-FC	Rapid 200	PEMFC	POLITO	[13]
2016	HY4	Pipistrel Taurus G4	PEMFC	DLR	[14,15]
2025	-	Dornier 228	Fuel cell	ZeroAvia	[16]
2025	328H2-FC	Dornier 328	PEMFC	DLR	[17,18]
2035	ZEROe	-	Direct combustion & fuel cell as APU	Airbus	[7]

In general, there are two ways in which hydrogen can be used as an energy source. First, it can be burned directly in gas turbines, like kerosene. This requires only minor changes to aircraft turbines, namely, turboprop and turbofan engines, but requires a newly designed fuel system [19,20]. As no carbon is used in the combustion, the production of the greenhouse gas CO_2 is completely avoided, while nitrogen oxides NO_x are significantly reduced [21]. Hydrogen also has a higher gravimetric density (33.33 kW h/kg) than kerosene (11.9 kW h/kg). However, the climate impact of hydrogen combustion in aircraft remains significant, mainly because of the high production of H_2O vapor which results in contrails and cirrus formations [21,22]. Furthermore, hydrogen's volumetric density as LH2 (2.4 kW h/L) is unfavorable compared to kerosene (9.5 kW h/L), as shown in Figure 1. This is only partially offset by the higher gravimetric density, resulting in larger tanks than in kerosene-powered aircraft, creating tank integration and configuration challenges. These problems are accentuated by efficiency issues relating to boil-off and heat losses [21].

Secondly, hydrogen can be used in conjunction with oxygen in fuel cells to generate electricity for propulsion or on-board power supply. When compared to gas turbines, the fuel cell is more efficient and less sensitive to descaling efforts [23,24], and its climate impact is substantially lower [22]. However, there is little to no experience of using fuel cells at the multiple megawatt scale; for example, an Airbus A320 needs approximately 40 MW for takeoff [25], which is needed for medium- to long-range aircraft propulsion [21]. However, for smaller aircraft with a shorter range, fuel cells could be used as the main energy source. This is shown, for example, in Table 1, which describes projects using smaller Dornier aircraft with fuel cells as their main energy source.

Given the aviation industry's superior expertise with gas turbines, direct hydrogen combustion appears to be the way forward, at least in the near future and for larger aircraft. However, it is still likely that fuel cells will be employed as auxiliary power units (APUs) in a hybrid system because of their higher efficiency compared to gas turbines. In addition, APUs have a lower power requirement, between approximately 90 kW (Airbus A320) and 450 kW (Boeing 787) [26], which makes fuel cells more feasible [24,27–29]. This is consistent with the projects presented in Table 1, where direct combustion is used for larger aircraft with the option of fuel-cell-based APUs.

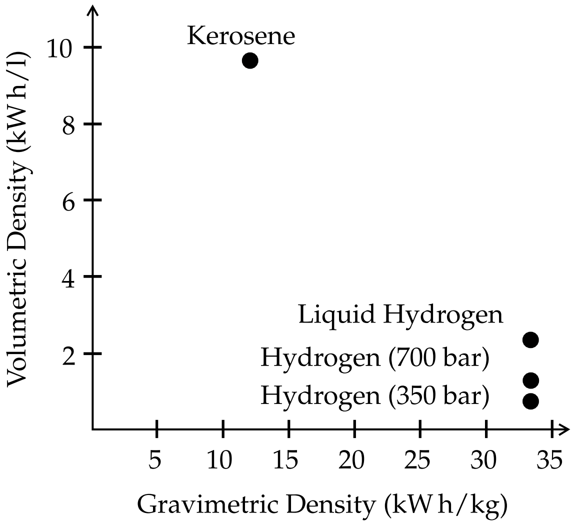

Figure 1. Volumetric and gravimetric density comparison between hydrogen and kerosene, data from Office of Energy Efficiency & Renewable Energy [30].

Fuel-cell-based APUs could also produce a higher share of the total energy needed for the aircraft than conventional APUs, in what are often called more-electric aircraft, allowing hydrogen-fueled or conventional gas turbines to be used only or mainly for propulsion energy [31–34]. This would enable designing of turbines that are more efficient because of missing secondary power losses and more precise operating conditions [33]. Schröder et al. [27] estimated a power range of several hundreds of kW for such fuel-cell APUs, while Campanari et al. [34] estimated ranges of up to 900–1500 kW for next generation APUs. Apart from electric power, fuel cells could provide products that are useful in an aircraft environment, such as water or oxygen-depleted air to inert fuel tanks [32,35–37].

However, a number of limiting factors are currently preventing the use of fuel cells in aircraft, such as the lack of hydrogen infrastructure at airports and increased safety requirements compared to other industries [24]. Contrary to popular belief, the power-to-weight ratio of fuel cells and the system surrounding them has now reached a theoretically satisfactory level, as their weight can be compensated for by higher efficiency [27,32]. The most crucial limiting elements, however, are production costs and durability. The latter is also strongly interconnected to degradation, reliability, longevity and service life [29,32,38–41]. While considerable work has been undertaken to address the production cost issue [42], and significant savings can be predicted as a result of future scaling effects [43], a solution to the service life problem has not been addressed to the same degree [44] and, therefore, is not currently in sight. MRO measures might and must contribute to such a solution, with the goal of prolonging service life and strengthening the reliability of fuel cells and, in consequence, achieving lower lifecycle cost [40,45,46].

This paper aims to help enable the use of fuel-cell systems in aviation applications. Therefore, it addresses the identified lifetime and reliability issues and presents a new perspective that has not been considered sufficiently in current production and design-oriented research. To achieve this, the paper will examine two consecutive research questions:

1. How can fuel cells be maintained, repaired, inspected and overhauled effectively in aviation?
2. How well are MRO providers equipped to perform the necessary MRO tasks from a business model standpoint?

The first question is addressed based on a literature review and comparison to the automotive sector. A more in depth technological analysis is conducted to provide further insight into challenges for fuel cell MRO in aviation. The second research question concerns especially the key resources of MRO providers, e.g., their supplier networks and repair and engineering capability, which are described and discussed in detail.

2. State of the Art of Fuel Cell MRO

While fuel cells may represent a relatively new technology for aviation purposes, much experience has been gained in other sectors with respect to fuel cell use. This includes selection of the right kind of fuel cell for a given application, which is specified in further analyzes described in the paper. Based on the type of fuel cell used, the importance of MRO can be assessed. Comparison with the automotive sector can offer further insights into fuel cell MRO.

2.1. Fuel Cell Types

There are various types of fuel cells, each with their own advantages and disadvantages. Therefore, it needs to be determined which fuel cell types are most relevant for aviation purposes and how they compare to fuel cells used in automotive applications.

It has been demonstrated that the polymer electrolyte membrane fuel cell (PEMFC) is the most promising type of fuel cell for aviation purposes [22,27,47] and is, therefore, used in most of the projects listed in Table 1. This is because of its high efficiency (40–60%), high power density (1.6 kW/kg), broad power application range (10 W up to 1 MW), fast start-up and shut-down times due to low operating temperature (60–90 °C), cold start and cold storage capability, as well as low noise emissions [8,34,48–50]. Another promising type of cell, which could be used in aviation, is the solid oxide fuel cell, which has a theoretically higher efficiency (60–65%) [33,48,51]. However, it is still underdeveloped for mobile applications [52]. Other fuel cells do not meet the power density and efficiency requirements for use in the aviation sector [8,48,50].

Since the commercialization of high-temperature PEMFCs is so far limited by their durability and considerable demand for platinum [53], the current literature suggests that low-temperature PEMFCs represent the most realistic option for future aviation fuel-cell applications [22,27,47]. The characteristics described make PEMFC particularly suitable for automotive applications, so that low-temperature PEMFC has become the dominant fuel-cell type in the automotive industry [42,54]. The following sections, therefore, focus on low-temperature PEMFCs.

2.2. Role of Fuel Cell MRO

The challenge created by the limited durability and reliability of fuel cells, introduced in Section 1, leads to particularly high demands and increased importance for MRO of PEMFCs. MRO can play a key role in mastering this challenge, but is only partially addressed in the current literature. The present focus of PEMFC MRO research is on prognostic health management (e.g., Wang et al. [55], He et al. [56], Chen et al. [57]) and has shifted from concern with degradation and performance effects in recent years (e.g., Li et al. [45], Gonnet et al. [58], Hashimasa and Numata [59]). In wider PEMFC research, there is a focus on production techniques, aimed at reducing the acquisition cost of PEMFCs (e.g., Department of Energy, U.S.A. [43]) and overcoming technical hurdles, especially the maximum energy output in the MW-scale (e.g., BALIS Project [60], 328H2-FC Project [18] and the ZEROe concept aircraft proposed by Airbus [7]). This research suggests that conventional maintenance activities, such as regular inspection, repair of defective parts and the scheduled replacement of components, has mostly been overlooked and neglected, even though fuel-cell maintenance can lead to significant lifetime extension [61]. This can mainly be explained by the fact that PEMFCs are not yet widely used. In the aviation industry, in particular, they have not progressed beyond the demonstration phase.

It is also difficult to compare the MRO of PEMFC based on experience in other industries. While MRO mostly follows the same principles and goals, such as ensuring operational readiness, cost reduction, complying with regulations and securing resale value, aviation MRO has the overarching goal of ensuring airworthiness and, thus, the safety of flight operations [62,63]. This leads to high safety and certification requirements and highly standardized processes, which do not occur to the same extent in most other industrial sectors. In terms of operations, fuel cells are often used in stationary applications for micro-combined-heat-and-power configurations and to achieve uninterruptible power supply [49]. These stationary applications involve different environments, MRO requirements, operational parameters and safety requirements, and lower maintenance requirements [64]. They do not, therefore, represent an ideal comparison to aviation. A theoretically interesting field, with a similar level of safety and certification standards, is the use of PEMFC on board naval vessels, especially submarines. While the use of PEMFC on ships is discussed but does not yet occur in practical applications, submarines use PEMFC for power generation [65]. However, as most of these applications are in the military sector, there is very limited access to data.

2.3. Fuel Cell MRO in Automotive and Aviation

In the automotive industry, PEMFCs are the standard for hydrogen-powered cars and buses and, even though the market share of fuel-cell-powered vehicles is still small [40,42], this has enabled experience to be acquired in the operation and MRO of PEMFCs, some of which is transferable to the aviation sector. Moreover, in the automotive sector, a similar concept to airworthiness exists, called road-worthiness. Although this is not as strict and internationalized in terms of regulation, it has resulted in similar certification and regulation measures. In particular, hydrogen-powered bus projects financed by the public sector provide a basis on which to build.

A commonality of both sectors is the use of fuel cells as a mobile power source. This results in exposure to challenging environments as fuel cells are sensitive to vibrations and shocks, which can lead to a variety of problems, such as gas leakage, structural damage and decreased voltage [39,66]. This can eventually necessitate replacement [65] or lead to operational failure [29]. The same is true for temperature and humidity fluctuations [29,66], though these are worse in aviation than in standard automotive applications, since they occur with greater frequency and with greater extreme value variations, especially with respect to cold temperatures.

Another point of similarity is the handling of hydrogen components in maintenance facilities. To work safely with hydrogen, automotive workshops have to be equipped accordingly, for example, requiring the use of hydrogen concentration sensors mounted below the ceiling. A critical concentration is normally defined as 20% of the lower explosion level of 4% hydrogen in air by volume; therefore 0.8% results in a pre-alarm, which is turned into a main alarm if the concentration doubles and reaches 1.6% [67]. When sensors detect a critical hydrogen concentration, a strong ventilation system should be turned on and/or additional vents should be opened if the roof design offers this capability. The ventilation system and vents must be located at the highest points in the ceiling area and be of explosion-proof design. Standard, non-explosion-proof electrical systems, including lighting, have to be automatically turned off in the event of a major alarm. This is accompanied by evacuation of all employees [67]. Similar regularities would require to be followed by MRO providers in hangars, who can, therefore, learn from experience acquired in the automotive sector.

Furthermore, personnel must be specially qualified for hydrogen system maintenance, both in the aviation and automotive sector. This requires technical training on the system and fault diagnostics with modern, computer-aided diagnostic tools, enabling checking and interpreting vehicle error and warning messages, as well as detection of leaks. Additionally, it is crucial to understand how to safely assemble and disassemble fittings, identify faulty screw connections, and work with valves, pressure reducers and damaged gas pipes, including knowing how to render the gas system inert. Employees must be instructed in the use of mobile gas detectors and be able to handle these detectors safely [67,68]. Safety measures and special qualifications for employees also have to be considered for work on electric systems, both in the automotive and aviation sector, as high voltages are present [67,69]. Theoretical layouts for an electric system in a fuel-cell-powered aircraft can be found in Eid et al. [70] and Hoenicke et al. [71]. When working with hydrogen systems, there is a great deal of common ground in both the aviation and automotive industries, which means that it is possible to build on qualification standards and measures that have already been developed.

There are also a number of differences between automotive and aviation applications. First, while the storage of gaseous hydrogen under high pressure at 700 bar for cars and 350 bar for buses is the standard in the automotive industry, in aviation liquefied hydrogen will be used. This is especially true for larger commercial aircraft [7,24], which are the focus of MRO and, thus, of this paper. However, smaller applications, such as unmanned aerial vehicles, can often use pressurized containers comparable to those used in the automotive sector [72]. Liquefied hydrogen is obtained by cooling gaseous hydrogen to 20 K [67]. This requires a fundamentally different type of tank and different system architecture and poses thermal isolation challenges [21,24]. As stated in Section 1, fuel cells in aviation will be required to deliver energy over a range of at least several hundreds of kilowatts, compared to below 100 kilowatts in most automotive applications. In addition, the power demand pattern of aircraft is different to that occurring in most cars. This is important, as the frequency and magnitude of cycling loads will decrease the durability of a fuel cell system [73]. Since the load in automotive applications is very dynamic [45], the target lifetime set by the U.S. Department of Energy is 8000 h [38]. In contrast, a service life of over 25,000 h has already been achieved for fuel-cell buses, mainly driven by more continuous power demand [74]. In aviation, long periods of continuous power demand will occur, e.g., during the cruise phase. However, dynamic load requirements are expected, especially during take-off and climb. Therefore, the target lifetime for the European Fuel Cells and Hydrogen Joint Undertaking is set to 20,000 h [75]. Because of the high safety standards in aviation, deriving from the concept of airworthiness, more redundant systems and higher safety margins will be required [24]. In addition, variation in the environmental pressure and inclination of the system during flight phases will occur, resulting in more challenging water management demands, especially with respect to the humidification of the fuel cell [35]. Together with higher energy demands and the use of LH2, these factors result in a drastic increase in system complexity.

As summarized in Table 2, there are significant differences between automotive and aviation applications of fuel cells in terms of general requirements, operational environment and MRO requirements. Therefore, a more in-depth analysis of the nature of MRO tasks is required.

Table 2. Summary of commonalities and differences in fuel-cell applications in the automotive and aviation sectors.

	Automotive	**Aviation**
General requirements		
Power Demand	<100 kW	>100’s kW
Power Demand Pattern	very dynamic	continuous with peaks
Type of Storage	gaseous at 350 or 700 bar	liquid at 20 K
Environmental		
Temperature Range	≈235–320 K	≈210–320 K
Temperature Fluctuation	low	high
Humidity Fluctuation	low	high
Atmospheric Pressure	≈1 bar	≈0.25–1 bar
Vibrations & Shocks	existent	existent
Inclination	occasional	at every flight
Maintenance specific		
Workshops	Special equipment required	Special equipment required
Employees	Specifically qualified	Specifically qualified
Goal	Road-worthiness among others	Focus on airworthiness

3. Technological Analysis of Fuel-Cell MRO in Aviation

To further analyze the PEMFC, the analysis is divided into two parts. PEMFCs transform the chemical energy liberated during the electrochemical reaction of hydrogen and oxygen into electrical energy, thermal energy and water. In practice, this requires a complex surrounding system, as shown in Figure 2. This includes, for example, the hydrogen supply and cooling, water management and electrical systems. First, the surrounding system is examined. Second, the core of the fuel cell, called the stack, is considered.

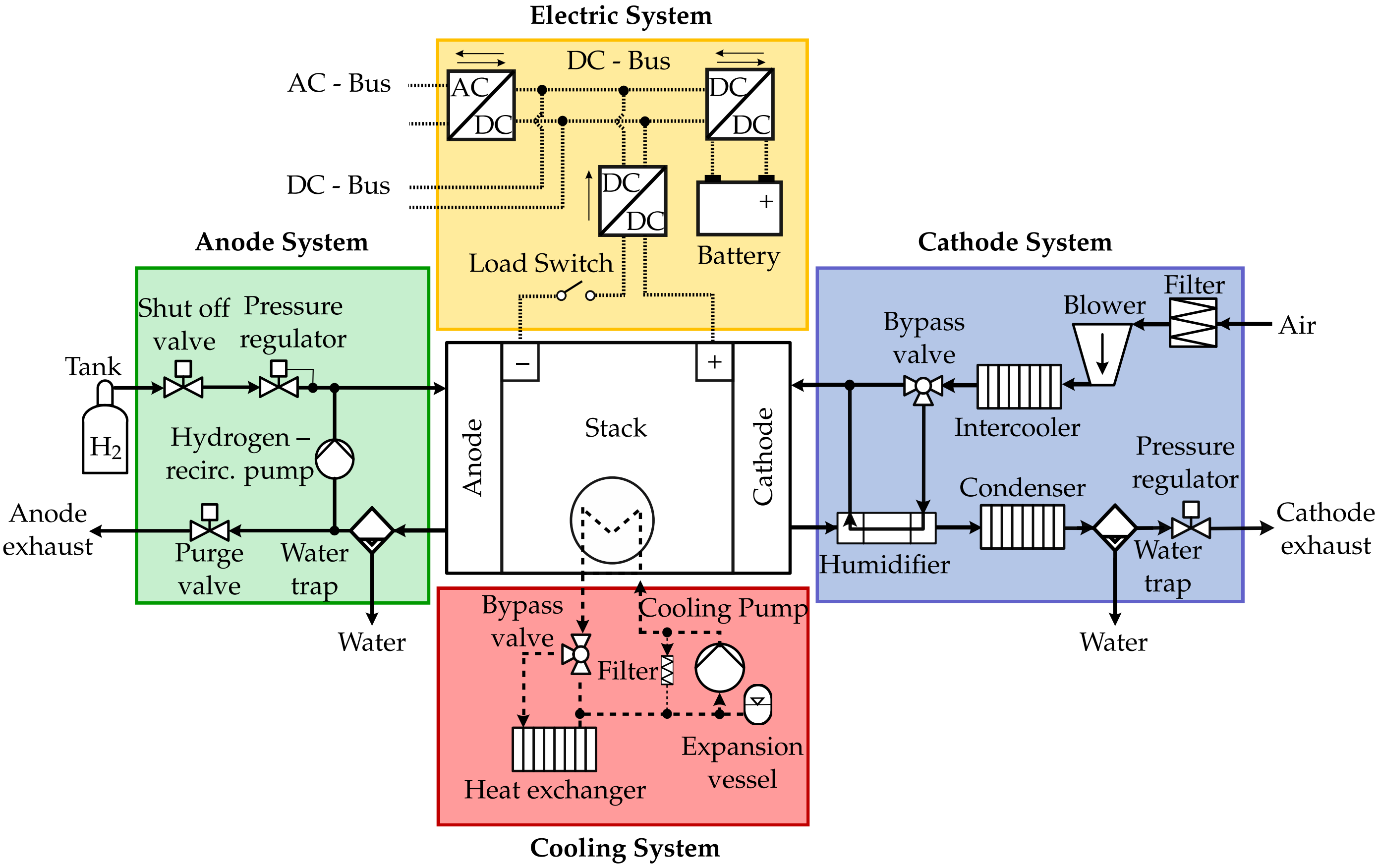

Figure 2. Exemplary illustration of a PEMFC, including stack and surrounding system.

3.1. Surrounding System

The system around the stack can vary in form and appearance, and, depending on the environment and application, different system components are required. For example, hydrogen is stored in metal hydride cylinders, while the oxygen is stored in liquefied form in submarine applications [65], a completely different approach from the previously discussed solution for aircraft. Specific layouts for commercial aviation PEMFC systems are, for example, described in Schröder et al. [27], Campanari et al. [34], Correa et al. [76], Lapeña-Rey et al. [77], while An et al. [72], Marinaro et al. [78], Suewatanakul et al. [79], Kim and Kwon [80], Bradley et al. [81] describe layouts for smaller unmanned aerial vehicles.

The electrical system that pulls electric power from the stack, the anode system that delivers hydrogen, the cathode system that delivers oxygen and discharges water, and the cooling system, are all shown in Figure 2. This layout will generally be the same for every PEMFC. However, the specific design and dimensioning of the components is a difficult task that depends heavily on the required applications and usage scenarios. For example, a battery is used to start the fuel-cell system because its auxiliary electrical power is needed for the initial supply of reactor gases and coolant to the system. Once hydrogen and oxygen are present in the stack, a cell potential builds up and the fuel cell system can supply electrical power. In addition, a battery can temporarily relieve the stack, for example, during the take-off and climb phases of an aircraft [71]. Thus, the stack can provide a base load while the batteries are used for peak loads. However, the optimal power ratio between battery and fuel cell depends on the application of the system and its usage profile. It can be seen that the surrounding system of the PEMFC and its design can become rather complex due to the number, dependencies and diversity of components. Furthermore, there are specific properties (explained in the following paragraph), which lead to significant challenges for the MRO of all components.

First of all, there are considerable thermal and pressure differences across the system. Schröder et al. [27], for example, proposed a pressure between approximately 0.25 and 1.75 bar across the system. Temperatures are lowest at 20 K in the tank, about 360 K at the fuel-cell inlet and calculated to be highest at around 500 K at the heat exchanger inlet. These thermal differences are strengthened by the fact that the ambient temperature can vary between 210 and 320 K during and outside aircraft operations, as shown in Table 2. Furthermore, hydrogen puts most materials under stress by permeating the surface, possibly causing embrittlement, especially in aviation materials such as aluminum, titanium and steel [8]. This has to be counteracted by careful material selection and regular maintenance [8,82].

Additionally, the presence of hydrogen creates unique safety risks in and around fuel cells. A first safety critical aspect is the dispersion of hydrogen gas. As a concentration of 4% hydrogen by volume in air is sufficient for an explosion, resulting in an alarm threshold of only 0.8%, and the minimum ignition energy of 0.02 mJ is very low, hydrogen leakage should be minimized as far as possible [41,83,84]. This is challenging, mainly because hydrogen molecules are significantly smaller than those of other gases and, therefore, pass through most materials, which results in increased leakage rates [41,84]. At the same time it is colorless, odorless and tasteless [83,84]. Therefore, an appropriate hydrogen sensor system must measure the concentration at any time, especially in the vicinity of sealed connections and vulnerable parts, particularly pumps and valves, in order to alert personnel and enable countermeasures to be taken [8,58,83].

Many of the individual parts are already in use in aviation (e.g., compressors, pumps, valves, cooling/heating systems, power electronics), albeit in different settings and magnitudes. The parts are also well known in several other industries and are thoroughly understood, for example, by the manufacturer. An exception are the LH2-tanks, as they are currently not used in any industry except aerospace. It can, therefore, be assumed that most parts are maintainable and previous knowledge from other industries can be transferred. Specific MRO tasks for PEMFCs in aviation are rare but, for example, are described by Wehrspohn et al. [31], based mainly on Lanz [85] and Saxe et al. [86], complemented by [87–91]. A theoretical maintenance schedule derived from these sources is presented in Table A1 in Appendix A. It should be noted that the exact intervals, whether provided from literature sources or based on assumptions, depend on the system layout and environmental circumstances and that other sources, such as Gonnet et al. [58], can deliver slightly different results. It can be seen that the circumstances described above result in frequent inspection tasks, as well as a large number of system tests. As the surrounding system of fuel cells includes parts that wear, e.g., filters, seals, valves and air compressors, scheduled replacement of parts is performed at every eighth A-check and all C-checks. There is potential to replace the high number of inspection tasks and tests with respect to the surrounding system of PEMFCs with a sophisticated condition monitoring system and concluding with condition based maintenance (CBM), as suggested by Knowles et al. [41] in 2010.

In sum, it can be stated that the surrounding system of a PEMFC consists of a large number of components, which are not exclusively used in fuel cell or aviation applications. However, their interdependencies and the unique environment can make their MRO challenging.

3.2. Stack

The stack is the core of the fuel cell. It is the part that converts chemical energy into electricity, heat and water. As such, it is the most complex subsystem, although it works passively and is completely reliant on the surrounding system [46]. A stack is built from numerous separate cells, with the exact number varying from a handful for low-power applications to several hundred for high-power applications, such as those required in aircraft. A more detailed picture is provided in Figure 3, which also shows that the number of parts needed to construct a single cell is limited. However, the cell incorporates many high-tech materials, such as membrane electrode assembly and valuable resources (e.g., a platinum catalytic layer). A detailed overview of the materials present in a PEMFC is provided by Miotti et al. [92], including future scenarios and developments. These materials make the stack the most valuable and expensive part of the PEMFC, representing around 50% of the entire PEMFC cost [40,93].

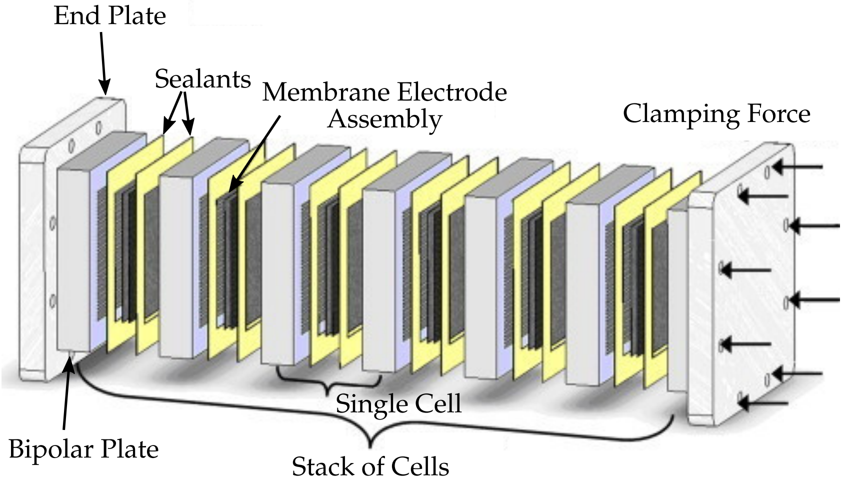

Figure 3. PEMFC stack. Reprinted from Journal of Power Sources, 194/1, Lin et al. [94], A high-efficiency assembly technique for large PEMFC stacks: Part I. Theory, 381–390, Copyright (2022), with permission from Elsevier.

The stack is subject to various degradation and damage mechanisms. The most relevant are flooding, drying, electrode poisoning, and fuel or air starvation [93]. The first describes a process where water is not evacuated properly from the inside of a cell, causing inhibition of the electrochemical reaction. On the other hand, evacuating too much water and dehumidifying a cell damages the membrane and blocks proton transport, resulting in the inhibition of the electrochemical reaction. This process is also called "dry out". The platinum catalytic layer, as part of the electrode, can be poisoned by carbon monoxide CO and sulfur hydroxide H_2S, which limits the reactivity of the cell. Every inhibition of the electrochemical reaction and reduction in cell reactivity will ultimately lead to reduced power output. The final damaging mechanism, starvation, occurs when insufficient reactants, either hydrogen or oxygen, are supplied to the active sites. Starvation leads to reduced power output and also to membrane damage. Such damage, which occurs because of operational parameters, can be caused by a damaged surrounding system. In particular, blocked or worn filters, damaged or leaking valves, a defective pressure regulator and problem with the humidifier, could cause and enhance such degradation and damage mechanisms [42,93,95].

Degradation and damage mechanisms can be avoided by modifying the stack's operating conditions. An overview of such measures is given in Table 3. Because most measures will affect the power output of the PEMFC, the power demand by electricity consumers may prohibit certain countermeasures. The avoidance mechanisms can have opposite effects on different damage mechanisms, especially drying and flooding. Therefore, the determination of the precise nature of any damage is critical.

Table 3. Overview of damage mitigation measures, adapted from Aubry et al. [93].

Flooding	Drying
Decrease relative humidity of inlet gases Increase flow of inlet gases Increase stack temperature Decrease current	Increase relative humidity of inlet gases Decrease flow of inlet gases Decrease stack temperature Increase current
Poisoning	**Starvation**
Increase air flow Air bleeding	Increase air flow Increase hydrogen flow Increase pressure

Modification of operation conditions can not only prevent damage, but even reverse some degradation and damage mechanisms. For example, high current pulses can reverse the poisoning of the catalyst layer [41]. The incursion of single cells into negative potential values due to hydrogen starvation is also partially reversible [96]. However, hydrogen shortage inside a cell should be prevented in any event by taking appropriate measures. Side-reactions of a short-term under-supply of oxygen can lead to faster activation or reconditioning of a cell, but can also result in a decline in power output [97]. Again, it should be noted that the stack is an interdependent system, so determining the nature of damage and its cause is important for selecting the appropriate countermeasure. Similar to the surrounding system, a sophisticated condition-monitoring system and suitable sensor technology will be required.

These issues are compounded by the lack of opportunity for visual inspection, mostly due to the extremely compact design of the stack and the miniature size of damage occurring. Other inspection technologies exist, namely electrochemical impedance spectroscopy (EIS) in conjunction with the use of a polarization curve, which can provide detailed information about the static and dynamic performance and health status of the stack [57] and enable conclusions to be drawn about the specific damage mechanism [96]. However, EIS only works if the fuel cell is operated in a steady state [98] and does not currently have the technological readiness level to be used in real-world environments [99]. It is obvious that only non-destructive diagnostic methods are permissible for MRO tasks. A thorough coverage of inspection technologies and diagnostic methods for PEMFCs stacks can be found in Wu et al. [100] and Wu et al. [101]. Ex situ examinations are reserved for scientific investigations. However, the knowledge gained here can be used with model-based methods, summarized by Lin et al. [102], to make predictive statements and enable condition monitoring.

Aviation fuel cells, including the stacks, are exposed to strong vibrations and mechanical shocks, as well as high thermal stresses, as described in Section 2. This favors the formation of pinholes, cracks and degradation mechanisms in the membrane. The effects of this damage are similar to flooding and drying and the damage itself is irreversible [29,44]. In the event of such damage to a single fuel cell, repair methods are very limited or non-existent [41,47]. The simplest option is to exchange the entire affected cell if it is detected to be outside of the predefined limits. This will mostly happen to cells near the beginning and especially the end of the stack, as they are more prone to damage [96]. Li et al. [45] showed that the exchange of damaged cells mitigated performance deterioration of a PEMFC, enabling refurbishment of fuel cells, which was less expensive than installing a new system [61]. However, exchange of a damaged cell has to be performed by a specialist [41], and, in most cases, the complete stack has to be shipped to the manufacturer [85]. The difficulty of cell replacement lies primarily in the correct assembly and, above all, in pressing the individual cell parts and the cells themselves onto each other.

4. Implications for MRO Providers

In relation to the second research question, the implications of implementing fuel cells in aviation for MRO providers are discussed below. A generic business model of an MRO provider is presented and adapted to the unique challenges of fuel cell MRO. Subsequently, the key resources of MRO providers are examined in-depth with regard to possible fuel-cell implementation.

4.1. Business Model

Despite the fact that the concept of business models is used extensively in research, it does not have an unequivocal definition [103–105]. In the following, the definition proposed in Osterwalder and Pigneur [106] is used:

> A business model describes the rationale of how an organization creates, delivers, and captures value [106].

According to this definition, the value proposition is the focal point of all business models. The other building blocks are the key partners, key activities, key resources, customer relationships, channels, customer segments, cost structure and the revenue streams [106]. Together they represent the business model canvas, developed by Osterwalder [107]. The canvas is used to answer the second research question due to its general and comprehensive character.

Figure 4 depicts a generic business model canvas for a classic MRO provider, closely adapted from Wirths [62], though the business model of a specific MRO provider may deviate from this generic approach. Reasons for this might include the degree of integration into an airline [108], the size of the MRO provider [62] and their customer segment [63].

Analyzing the individual building blocks indicates that some of them are unaffected by implementation of fuel cells in aviation. This accounts for the customer segments, customer relationship and channels. The same is true for the core of the business model, the value proposition of MRO providers. The key activities are also unaffected. The suppliers may change and grow in quantity because fuel cells are not yet manufactured by traditional aviation firms. Some traditional aviation companies plan to build their own fuel cells, for example, the Airbus joint venture Aerostack [109] and the "Flying Fuel Cell" from MTU [110]. The growth in suppliers is primarily attributed to the complex layout of the PEMFC surrounding system, which is unknown in today's aviation industry, as analyzed in Section 3.1. Therefore, a component management issue may emerge that proves to be more challenging for the MRO provider. This is accentuated by the fact that many components will be maintained by the manufacturing supplier. However, because MRO providers have considerable experience in working with a large number of component suppliers, and aircraft have traditionally been complex systems, the effects of PEMFCs complexity and a small number of new suppliers should be limited.

Changes to cost structure and revenue streams are difficult to predict. This is primarily due to a complete absence of data on MRO of PEMFCs [40]. An approximate calculation is provided in Wehrspohn et al. [31], where the total MRO cost of an aircraft is calculated. A PEMFC is used as an APU with a higher energy share than modern APUs; a likely scenario already introduced in Section 1, is used as a basis. Depending on the scenarios, which are mostly determined by the LH2-tank, an increase in the MRO cost from 5 to 37% is calculated. While the higher estimates are primarily attributable to the required exchange of the entire fuel tank during the lifecycle of the aircraft, it is nevertheless demonstrated that, under the assumed boundary conditions, no MRO cost reduction should be expected as a result of implementing fuel cells [31]. This is supported by the fact that automotive fuel cell vehicles are more expensive to maintain than conventional cars [61]. For MRO providers, this would result in a continuous revenue stream. The authors of Wang et al. [40] emphasize the potential increase in MRO cost following the implementation of fuel cells. The substantial costs associated with disassembling the stack for repair are particularly highlighted. These are projected to be up to 22% of the whole stack cost and will occur every time the stack has to be disassembled [40]. This is especially relevant for the exchange of individual fuel cells to increase stack performance, as described in Section 3.2.

Key Partners
- Affiliated airline
- Maintenance, Repair and Overhaul (MRO) providers
- Suppliers
- Original Equipment Manfucaturers

Key Activities
- Operational services: Line-, Base, Engine-, Components repair and aircraft engineering
- Development of alternative parts and repairs
- Process optimization

Key Resources
- Maintenance network including suppliers
- Operator experience
- Serviced fleet
- Financial strength
- Tangible and intangible manufacturing-specific resources
- Multi-vendor capability
- Repair and engineering capability
- Data processing and interpretation capability

Value Proposition
- Airworthiness assurance
- Reduction of Direct Maintenance Costs
- Service Quality
- Broad portfolio of basic and advanced services across aircraft plattforms
- Airline (costumer) perspective

Costumer Relationship
- Often: long-term relationship driven by trust, cooperation and cost efficiency
- Low level of long-term dependence of airline on MRO provider

Channels
- Key account manager for dedicated personal assistance predominant
- Other channels (e.g. aircraft-on-ground desk) present

Costumer Segments
- Airlines
- Aircraft lessees and lessors

Cost Structure
- Cost Structure varies with services segment, averaging at 48% labor, 46% material, 7% services
- Lower cost base by use of alternative repair methods and parts

Revenue Streams
- Time and material-based revenue streams
- Market growth mainly in specific regions
- Segment growth mainly Engine- and Component MRO

Figure 4. Generic business model canvas for an MRO provider. Reproduced with permission from Wirths [62].

With respect to the cost structure, no data-based statements can be made. It could be that the use of high-value materials, as described in Section 3.2, will raise the share of material costs. Components containing such materials will need to be replaced many times during the aircraft lifecycle. For example, Wehrspohn et al. [31] estimate five PEMFC stacks, with a lifetime of 20,000 h, during an aircraft lifecycle of 32 years. This potentially opens the door to a valuable end-of-life (EoL) treatment of such components. This can include reselling to lower requirement applications or recycling of materials, particularly the high value and highly recyclable metal platinum [31]. Such EoL management could also significantly reduce the environmental impact of PEMFC [31,111] and represent a new revenue stream for MRO providers.

In order to further evaluate the individual changes to cost structure and revenue streams, methods in the area of cost analysis offer helpful tools for an MRO provider. In the EoL treatment example, these methods would help understanding of whether the additional expenditure to expand building blocks, such as key activities and value propositions, would be financially beneficial. Detailed analyses of the lifecycle cost of fuel-cell systems would also allow the MRO provider to identify material- or labor-intensive tasks. In combination, these methods can provide a basis for an individual MRO provider to prioritize future fuel-cell maintenance activities.

4.2. Key Resources

The most significant changes to the status quo must be anticipated in the key resources building block of the business model canvas. The key resources describe a business's most important assets [106] and include key capabilities [107] needed to deploy them [112].

A thorough comprehension of the surrounding system and the stack itself is essential for MRO of fuel cells. It is first important to understand that PEMFCs are highly reliant on the operating conditions, as explained in Section 3.2. Because some damage mechanisms can be reversed by altering operating conditions, MRO providers should have the technical capability to perform such procedures. However, because these methods differ fundamentally from state-of-the-art maintenance procedures, they have to be explored during the design and certification process and developed through operational experience in order to describe them in manuals, such as the "Aircraft Operating Manual" and "Aircraft Maintenance Manual", and eventually be used in practice. This concerns the stack particularly as it is the most complex component. Depending on the overall system design and designated redundancies, the stack may also be a critical safety component. Furthermore, it is the most expensive component of a PEMFC and, therefore, of high economic relevance for the aircraft operator as well as MRO providers. Possible conflicts could occur because the MRO of stacks is mostly in the hands of the corresponding supplier. However, as shown in Wirths [62], this is a regular occurrence in the MRO industry, as suppliers are frequently the only source of necessary resources for MRO tasks.

Focusing on Figure 4, the key resources "tangible and intangible manufacturing-specific resources" and "repair and engineering capability" are particularly affected as MRO providers would have to expand these resources to the area of fuel cells. The deployment of fuel cells will most likely have a significant impact on "data processing and interpretation capability". Because of the significant effect of operating conditions on system health, acquiring and analyzing the operating data is crucial. This is accentuated by the missing inspection possibilities for the stack, making it necessary to interpret operational data correctly. As a result, sophisticated competencies in the areas of condition monitoring and concluding CBM need to be expanded.

5. Conclusions

In this paper, two consecutive research questions were addressed. First, based on a literature review, including a comparison between aviation and automotive fuel-cell applications, and a thorough examination of PEMFCs in aviation, it was shown that fuel cells can be maintained, repaired and overhauled effectively. MRO tasks for the stack are limited to replacement of single damaged fuel cells and alteration of the operating conditions. In the surrounding system, it can be assumed that most components are easily maintainable due to the transferable experience from other industries. Second, it was shown that the business model and the capabilities of MRO providers, in principle, enables them to perform MRO tasks for fuel cells. However, the key resources have to be adapted to apply the technical capabilities to the field of fuel-cell MRO. This includes prioritizing data-processing and interpretation capabilities. A competent MRO can enable the implementation of fuel cells in aviation since it is the foundation for solving the challenge of durability. As a result, MRO providers will play an important role in implementation because MRO is inextricably linked to other key issues, such as system safety and certification. Future research activities should emphasise MRO when assessing the feasibility of hydrogen systems for use in aviation. This includes consideration of MRO when comparing different fuel-cell types, sophisticated life-cycle analysis for environmental impacts, as well as lifetime and life-cycle comparison to assess the economic and operational effects. MRO should always be considered when researching these and other hydrogen-related topics to support the aviation industry in achieving its decarbonization goals.

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Appendix A

Table A1. Overview of all necessary maintenance tasks for an aircraft using PEMFC in combination with LH2 as an APU (without consideration of tank maintenance). Reproduced with permission from DLR e.V. [31].

Check	Interval	Task Description	MH [h]	Downtime [h]
Daily	every	Check ground fault monitor resistance and replace water or de-ionizing filter if required	1.25	0.25
		Check stack vent fans Inspect burst disk vent cap		
		Check leak indicators and sensors, and calibrate system if required		
		Check for fluid leaks or puddles		
		Inspect air intake, air exhaust and canopies		
Weekly	every	Perform leak-down test	4.5	1
		Check cell voltage monitor		
		Perform fuel delivery circuit leak test		
		Inspect fire suppression sensors		
		Clean stack vent fan filters		
		Inspect stack air inlet filters and replace if required		
		Inspect filter minder and replace air intake filter if indicated		
		Check stack coolant level		
		Inspect hoses and tubes		
A-Check	every	Perform fuel cell external and transfer leak tests	20	10
		Perform glycol system integrity test		
		Check power cable connections		
		Perform high- and motive-pressure circuit leak test		
		Inspect high, motive and fuel delivery circuit components		
		Compare fuel pressure transducer readings		
		Inspect radiator		

Table A1. *Cont.*

Check	Interval	Task Description	MH [h]	Downtime [h]
A-Check	every 2nd	Check the motive pressure regulator solenoid valve Perform ground integrity tests	10	10
		Inspect and/or replace air intake filter		
	every 4th	Inspect heat exchanger (vaporizer)	80	10
		Inspect primary and secondary relive valve and vent line		
		Inspect pressure regulator and boost pumps		
		Inspect vacuum pump system, N_2 purge system and high pressure pump		
		Inspect burst discs		
	every 8th	Replace pressure regulator diaphragm, seal replacement	20	10
		Perform fire suppression system tests		
		Inspect power train and stack vibration mounts		
C-Check	every	Exchange of humidifier	9	3
	every 2nd	Exchange of compressor	9	3
	every 3rd	Exchange of primary and secondary relive valve and vent line	30	5
		Exchange of pressure regulator and boost pumps		
		Exchange of heat exchanger (vaporizer)		
		Exchange of vacuum pump system, N_2 purge system and high pressure pump		
		Exchange of burst disc		
	every 4th	Exchange of fuel-cell stacks and compressor power converter	72	24

References

1. International Air Transport Association. Fact Sheet: Climate Change & CORSIA. Available online: https://www.iata.org/contentassets/713a82c7fbf84947ad536df18d08ed86/fact-sheet-climate-change.pdf (accessed on 11 November 2022).
2. International Air Transport Association. Our Commitment to Fly Net Zero by 2050. Available online: https://www.iata.org/en/programs/environment/flynetzero/ (accessed on 11 November 2022).
3. International Civil Aviation Organization. Consolitated Statement of Continuing ICAO Policies and Practices Related to Environmental Protection Climate Change: Resolution A40-18. Available online: https://www.icao.int/environmental-protection/Documents/Assembly/Resolution_A40-18_Climate_Change.pdf (accessed on 11 November 2022).
4. European Commission. Reducing Emissions from Aviation. Available online: https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-aviation_en (accessed on 11 November 2022).
5. European Commission. Directorate-General for Mobility and Transport, Directorate-General for Research and Innovation. In *Flightpath 2050: Europe's Vision for Aviation: Maintaining Global Leadership and Serving Society's Needs*; Publications Office: Brussels, Belgium, 2011. [CrossRef]
6. Rao, A.G.; Yin, F.; Werij, H. Energy Transition in Aviation: The Role of Cryogenic Fuels. *Aerospace* **2020**, *7*, 181. [CrossRef]
7. Airbus. ZEROe: Towards the World's First Zero-Emission Commercial Aircraft. Available online: https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe (accessed on 9 November 2022).
8. Bruce, S.; Temminghoff, M.; Hayward, J.; Palfreyman, D.; Munnings, C.; Burke, N.; Creasey, S. Opportunities for Hydrogen in Commercial Aviation—CSIRO. Available online: https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy-and-Resources/hydrogen-commercial-aviation (accessed on 10 November 2022).
9. Boeing Prepares Fuel Cell Demonstrator Airplane for Ground and Flight Testing. Available online: https://boeing.mediaroom.com/2007-03-27-Boeing-Prepares-Fuel-Cell-Demonstrator-Airplane-for-Ground-and-Flight-Testing (accessed on 9 November 2022).
10. Boeing Successfully Flies Fuel Cell-Powered Airplane. Available online: https://www.boeing.com/aboutus/environment/environmental_report/_inc/flash-2-1-2.html (accessed on 9 November 2022).

11. DLR and Airbus Testing Hydrogen PEM Fuel Cell Auxiliary Power System in A320. Available online: https://www.greencarcongress.com/2008/05/dlr-and-airbus.html (accessed on 9 November 2022).
12. Antares DLR-H2—Out of opEration. Available online: https://www.dlr.de/content/en/articles/aeronautics/research-fleet-infrastructure/dlr-research-aircraft/antares-dlr-h2-out-of-operation.html (accessed on 9 November 2022).
13. ENvironmentally Friendly Inter City Aircraft powered by Fuel Cells (ENFICA-FC). Available online: http://www.enfica-fc.polito.it/ (accessed on 9 November 2022).
14. HY4 Aircraft. Available online: https://www.aerospace-technology.com/projects/hy4-aircraft/ (accessed on 9 November 2022).
15. Choi, Y.; Lee, J. Estimation of Liquid Hydrogen Fuels in Aviation. *Aerospace* **2022**, *9*, 564. [CrossRef]
16. ZeroAvia Homepage. Available online: https://www.zeroavia.com/ (accessed on 11 November 2022).
17. Deutsche Aircraft aims for hydrogen aviation. *Fuel Cells Bull.* **2021**, *2021*, 7. [CrossRef]
18. Deutsches Zentrum für Luft- und Raumfahrt e.V. BMWK fördert Projekt zur Weiterentwicklung der Wasserstoff-Brennstoffzellen-Technologie. Available online: https://www.dlr.de/content/de/artikel/news/2022/02/20220405-projekt-weiterentwicklung-wasserstoff-brennstoffzellen-technologie.html (accessed on 11 November 2022).
19. Chiesa, P.; Lozza, G.; Mazzocchi, L. Using Hydrogen as Gas Turbine Fuel. *J. Eng. Gas Turbine Power* **2005**, *127*, 73–80. [CrossRef]
20. Haglind, F.; Singh, R. Design of Aero Gas Turbines Using Hydrogen. *J. Eng. Gas Turbine Power* **2006**, *128*, 754–764. [CrossRef]
21. Baharozu, E.; Soykan, G.; Ozerdem, M.B. Future aircraft concept in terms of energy efficiency and environmental factors. *Energy* **2017**, *140*, 1368–1377. [CrossRef]
22. Publications Office of the European Union. *Hydrogen-Powered Aviation: A Fact-Based Study of Hydrogen Technology, Economics, and Climate Impact by 2050*; Publications Office: Luxembourg, 2020. [CrossRef]
23. Lindorfer, J.; Reiter, G.; Tichler, R.; Steinmüller, H. 14—Hydrogen fuel, fuel cells, and methane. In *Managing Global Warming*; Letcher, T.M., Ed.; Elsevier Science & Technology: San Diego, CA, USA, 2018; pp. 419–453. [CrossRef]
24. Hoelzen, J.; Silberhorn, D.; Zill, T.; Bensmann, B.; Hanke-Rauschenbach, R. Hydrogen-powered aviation and its reliance on green hydrogen infrastructure—Review and research gaps. *Int. J. Hydrogen Energy* **2022**, *47*, 3108–3130. [CrossRef]
25. Rindlisbacher, T. Auf dem Weg zum klimafreundlichen Fliegen. Available online: https://www.ssm-studies.ch/fileadmin/pdf/SSM/Blogsammlung/Antriebstechnologien/200804_Auf_dem_Weg_zum_klimafreundlichen_Fliegen.pdf (accessed on 11 November 2022).
26. Sforza, P.M. Chapter 8—Refined Weight and Balance Estimate. In *Commercial Airplane Design Principles*; Sforza, P.M., Ed.; Butterworth-Heinemann: Boston, MA, USA, 2014; pp. 301–347. [CrossRef]
27. Schröder, M.; Becker, F.; Kallo, J.; Gentner, C. Optimal operating conditions of PEM fuel cells in commercial aircraft. *Int. J. Hydrogen Energy* **2021**, *46*, 33218–33240. [CrossRef]
28. Agostini, A.; Belmonte, N.; Masala, A.; Hu, J.; Rizzi, P.; Fichtner, M.; Moretto, P.; Luetto, C.; Sgroi, M.; Baricco, M. Role of hydrogen tanks in the life cycle assessment of fuel cell-based auxiliary power units. *Appl. Energy* **2018**, *215*, 1–12. [CrossRef]
29. Banan, R.; Bazylak, A.; Zu, J. Combined effects of environmental vibrations and hygrothermal fatigue on mechanical damage in PEM fuel cells. *Int. J. Hydrogen Energy* **2015**, *40*, 1911–1922. [CrossRef]
30. Office of Energy Efficiency & Renewable Energy. Hydrogen Storage. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-storage (accessed on 11 November 2022).
31. Wehrspohn, J.; Rahn, A.; Papantoni, V.; Silberhorn, D.; Burschyk, T.; Schröder, M.; Linke, F.; Dahlmann, K.; Kühlen, M.; Wicke, K.; et al. A Detailed and Comparative Economic Analysis of Hybrid-Electric Aircraft Concepts Considering Environmental Assessment Factors. In Proceedings of the AIAA Aviation Forum, Chicago, IL, USA, 27 June–1 July 2022; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2022. [CrossRef]
32. Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU): Addendum to the Multi—Annual Work Plan 2014–2020. Available online: https://www.fch.europa.eu/sites/default/files/MAWP%20final%20version_endorsed%20GB%2015062018%20%28ID%203712421%29.pdf (accessed on 11 November 2022).
33. Whyatt, G.A.; Chick, L.A. Electrical Generation for More-Electric Aircraft Using Solid Oxide Fuel Cells. Available online: https://www.energy.gov/sites/default/files/2014/03/f9/sofc_for_aircraft_pnnl_2012.pdf (accessed on 11 November 2022).
34. Campanari, S.; Manzolini, G.; Beretti, A.; Wollrab, U. Performance Assessment of Turbocharged Pem Fuel Cell Systems for Civil Aircraft Onboard Power Production. *J. Eng. Gas Turbine Power* **2008**, *130*, 021701. [CrossRef]
35. Dyantyi, N.; Parsons, A.; Bujlo, P.; Pasupathi, S. Behavioural study of PEMFC during start-up/shutdown cycling for aeronautic applications. *Mater. Renew. Sustain. Energy* **2019**, *8*, 4. [CrossRef]
36. Keim, M.; Kallo, J.; Friedrich, K.A.; Werner, C.; Saballus, M.; Gores, F. Multifunctional fuel cell system in an aircraft environment: An investigation focusing on fuel tank inerting and water generation. *Aerosp. Sci. Technol.* **2013**, *29*, 330–338. [CrossRef]
37. Renouard-Vallet, G.; Saballus, M.; Schumann, P.; Kallo, J.; Friedrich, K.A.; Müller-Steinhagen, H. Fuel cells for civil aircraft application: On-board production of power, water and inert gas. *Chem. Eng. Res. Des.* **2012**, *90*, 3–10. [CrossRef]
38. Department of Energy, U.S.A. Automotive Fuel Cell Targets and Status. Available online: https://www.hydrogen.energy.gov/pdfs/20005-automotive-fuel-cell-targets-status.pdf (accessed on 11 November 2022).
39. Haji Hosseinloo, A.; Ehteshami, M.M. Shock and vibration effects on performance reliability and mechanical integrity of proton exchange membrane fuel cells: A critical review and discussion. *J. Power Sources* **2017**, *364*, 367–373. [CrossRef]
40. Wang, J.; Wang, H.; Fan, Y. Techno-Economic Challenges of Fuel Cell Commercialization. *Engineering* **2018**, *4*, 352–360. [CrossRef]

41. Knowles, M.; Baglee, D.; Morris, A.; Ren, Q. The State of the Art in Fuel Cell Condition Monitoring and Maintenance. *World Electr. Veh. J.* **2010**, *4*, 487–494. [CrossRef]
42. Alaswad, A.; Omran, A.; Sodre, J.R.; Wilberforce, T.; Pignatelli, G.; Dassisti, M.; Baroutaji, A.; Olabi, A.G. Technical and Commercial Challenges of Proton-Exchange Membrane (PEM) Fuel Cells. *Energies* **2021**, *14*, 144. [CrossRef]
43. Department of Energy, U.S.A. Fuel Cell System Cost—2017. Available online: https://www.hydrogen.energy.gov/pdfs/17007_fuel_cell_system_cost_2017.pdf (accessed on 11 November 2022).
44. Whiteley, M.; Dunnett, S.; Jackson, L. Failure Mode and Effect Analysis, and Fault Tree Analysis of Polymer Electrolyte Membrane Fuel Cells. *Int. J. Hydrogen Energy* **2016**, *41*, 1187–1202. [CrossRef]
45. Li, X.; Li, J.; Xu, L.; Yang, F.; Hua, J.; Ouyang, M. Performance analysis of proton-exchange membrane fuel cell stacks used in Beijing urban-route buses trial project. *Int. J. Hydrogen Energy* **2010**, *35*, 3841–3847. [CrossRef]
46. Liang, J.M.; Jian, Q.F. Decay Analysis of a 5kW PEMFC Stack in Sightseeing Bus. *Appl. Mech. Mater.* **2013**, *401-403*, 1826–1829. [CrossRef]
47. Placca, L.; Kouta, R. Fault tree analysis for PEM fuel cell degradation process modelling. *Int. J. Hydrogen Energy* **2011**, *36*, 12393–12405. [CrossRef]
48. Kazula, S.; de Graaf, S.; Enghardt, L. Review of Fuel Cell Technologies and Evaluation of their Potential and Challenges for Electrified Propulsion Systems in Commercial Aviation. In Proceedings of the Global Power and Propulsion Society 2022, Chania, Greece, 12–14 September 2022. [CrossRef]
49. Cigolotti, V.; Genovese, M.; Fragiacomo, P. Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems. *Energies* **2021**, *14*, 4963. [CrossRef]
50. Bernay, C.; Marchand, M.; Cassir, M. Prospects of different fuel cell technologies for vehicle applications. *J. Power Sources* **2002**, *108*, 139–152. [CrossRef]
51. Tornabene, R.; Wang, X.Y.; Steffen, C.J., Jr.; Freeh, J.E. Development of Parametric Mass and Volume Models for an Aerospace SOFC/Gas Turbine Hybrid System. Available online: https://ntrs.nasa.gov/api/citations/20050203845/downloads/20050203845.pdf (accessed on 11 November 2022).
52. Fernandes, M.D.; Andrade, S.D.P.; Bistritzki, V.N.; Fonseca, R.M.; Zacarias, L.G.; Gonçalves, H.; de Castro, A.F.; Domingues, R.Z.; Matencio, T. SOFC-APU systems for aircraft: A review. *Int. J. Hydrogen Energy* **2018**, *43*, 16311–16333. [CrossRef]
53. Hjuler, H.A.; Azizi, K.; Seselj, N.; Martinez Alfaro, S.; Garcia, H.R.; Gromadskyi, D.; Hromadska, L.; Primdahl, S.; Jensen, J.O.; Li, Q.; et al. High-Temperature PEM Fuel Cells: Towards Decreasing the Pt Loadings. *Meet. Abstr.* **2021**, *MA2021-02*, 1196. [CrossRef]
54. Mokrani, Z.; Rekioua, D.; Mebarki, N.; Rekioua, T.; Bacha, S. Proposed energy management strategy in electric vehicle for recovering power excess produced by fuel cells. *Int. J. Hydrogen Energy* **2017**, *42*, 19556–19575. [CrossRef]
55. Wang, C.; Li, Z.; Outbib, R.; Dou, M.; Zhao, D. A novel long short-term memory networks-based data-driven prognostic strategy for proton exchange membrane fuel cells. *Int. J. Hydrogen Energy* **2022**, *47*, 10395–10408. [CrossRef]
56. He, K.; Zhang, C.; He, Q.; Wu, Q.; Jackson, L.; Mao, L. Effectiveness of PEMFC historical state and operating mode in PEMFC prognosis. *Int. J. Hydrogen Energy* **2020**, *45*, 32355–32366. [CrossRef]
57. Chen, K.; Laghrouche, S.; Djerdir, A. Aging prognosis model of proton exchange membrane fuel cell in different operating conditions. *Int. J. Hydrogen Energy* **2020**, *45*, 11761–11772. [CrossRef]
58. Gonnet, A.E.; Robles, S.; Moro, L. Performance study of a PEM fuel cell. *Int. J. Hydrogen Energy* **2012**, *37*, 14757–14760. [CrossRef]
59. Hashimasa, Y.; Numata, T. Comparison of test results on load cycle durability of polymer electrolyte fuel cell cathode catalysts. *Int. J. Hydrogen Energy* **2015**, *40*, 11543–11549. [CrossRef]
60. Deutsches Zentrum für Luft- und Raumfahrt e.V. Project BALIS—DLR Is Developing and Testing Fuel Cells in the Megawatt Range for Air Transport. Available online: https://www.dlr.de/content/en/articles/news/2021/01/20210121_balis-project-funding.html (accessed on 11 November 2022).
61. Fuel Cell Maintenance and the "Moving Parts" Fallacy. Available online: https://www.ballardmotivesolutions.com/insights/fuel-cell-maintenance-and-the-moving-parts-fallacy (accessed on 9 November 2022).
62. Wirths, O. Business Model Innovation in the Aerospace Industry: Strategic Options for Maintenance, Repair and Overhaul Firms. Ph.D. Thesis, Universität zu Köln, Köln, Germany, 2019.
63. Viera, D.R.; Loures, P.L. Maintenance, Repair and Overhaul (MRO) Fundamentals and Strategies: An Aeronautical Industry Overview. *Int. J. Comput. Appl.* **2016**, *135*, 21–29. [CrossRef]
64. Laporte, A. Fact Sheet | Fuel Cells. Available online: https://www.eesi.org/papers/view/fact-sheet-fuel-cells (accessed on 11 November 2022).
65. Han, J.; Charpentier, J.F.; Tang, T. State of the art of fuel cells for ship applications. In Proceedings of the IEEE International Symposium on Industrial Electronics, Hangzhou, China, 28–31 May 2012; pp. 1456–1461. [CrossRef]
66. Hou, Y.; Hao, D.; Shen, J.; Li, P.; Zhang, T.; Wang, H. Effect of strengthened road vibration on performance degradation of PEM fuel cell stack. *Int. J. Hydrogen Energy* **2016**, *41*, 5123–5134. [CrossRef]
67. Deutsche Gesetzliche Unfallversicherung. Wasserstoffsicherheit in Werkstätten: DGUV Regel 209-072. Available online: https://publikationen.dguv.de/regelwerk/dguv-informationen/265/wasserstoffsicherheit-in-werkstaetten (accessed on 11 November 2022).

68. Deutsche Gesetzliche Unfallversicherung. Gasantriebsysteme in Fahrzeugen-Qualifizierung für Arbeiten an Fahrzeugen mit Gasantrieb: FBHM-099. Available online: https://publikationen.dguv.de/regelwerk/fachbereich-aktuell/holz-und-metall/3528/fbhm-099-gasantriebsysteme-in-fahrzeugen-qualifizierung-fuer-arbeiten-an-fahrzeugen-mit-gasantrieb (accessed on 11 November 2022).
69. Thomson, R.; Weichenhain, U.; Sachdeva, N.; Kaufmann, M. Hydrogen: A Future Fuel for Aviation? Available online: https://www.rolandberger.com/en/Insights/Publications/Hydrogen-A-future-fuel-for-aviation.html (accessed on 11 November 2022).
70. Eid, A.; El-Kishky, H.; Abdel-Salam, M.; El-Mohandes, T. Modeling and characterization of an aircraft electric power system with a fuel cell-equipped APU paralleled at main AC bus. In Proceedings of the IEEE International Power Modulator and High Voltage Conference 1, Atlanta, GA, USA, 23–27 May 2010; pp. 229–232. [CrossRef]
71. Hoenicke, P.; Ghosh, D.; Muhandes, A.; Bhattacharya, S.; Bauer, C.; Kallo, J.; Willich, C. Power management control and delivery module for a hybrid electric aircraft using fuel cell and battery. *Energy Convers. Manag.* **2021**, *244*, 114445. [CrossRef]
72. An, J.H.; Kwon, D.Y.; Jeon, K.S.; Tyan, M.; Lee, J.W. Advanced Sizing Methodology for a Multi-Mode eVTOL UAV Powered by a Hydrogen Fuel Cell and Battery. *Aerospace* **2022**, *9*, 71. [CrossRef]
73. Pahon, E.; Jemei, S.; Steiner, N.Y.; Hissel, D. Effect of Load Cycling on the Performance of Fuel Cell Stacks. In Proceedings of the 2019 IEEE Vehicle Power and Propulsion Conference (VPPC), Hanoi, Vietnam, 14–17 October 2019; pp. 1–4. [CrossRef]
74. Department of Energy, U.S.A. On-Road Transit Bus Fuel Cell Stack Durability. Available online: https://www.hydrogen.energy.gov/pdfs/20008-fuel-cell-bus-durability.pdf (accessed on 11 November 2022).
75. Multi-Annual Work Program 2014–2020. Available online: https://www.fch.europa.eu/sites/default/files/FCH%202%20JU%20MAWP-%20final%20%28ID%204221004%29.pdf (accessed on 11 November 2022).
76. Correa, G.; Borello, F.; Santarelli, M. Sensitivity analysis of temperature uncertainty in an aircraft PEM fuel cell. *Int. J. Hydrogen Energy* **2011**, *36*, 14745–14758. [CrossRef]
77. Lapeña-Rey, N.; Mosquera, J.; Bataller, E.; Ortí, F. First Fuel-Cell Manned Aircraft. *J. Aircr.* **2010**, *47*, 1825–1835. [CrossRef]
78. Marinaro, G.; Di Lorenzo, G.; Pagano, A. From a Battery-Based to a PEM Fuel Cell-Based Propulsion Architecture on a Lightweight Full Electric Aircraft: A Comparative Numerical Study. *Aerospace* **2022**, *9*, 408. [CrossRef]
79. Suewatanakul, S.; Porcarelli, A.; Olsson, A.; Grimler, H.; Chiche, A.; Mariani, R.; Lindbergh, G. Conceptual Design of a Hybrid Hydrogen Fuel Cell/Battery Blended-Wing-Body Unmanned Aerial Vehicle—An Overview. *Aerospace* **2022**, *9*, 275. [CrossRef]
80. Kim, T.; Kwon, S. Design and development of a fuel cell-powered small unmanned aircraft. *Int. J. Hydrogen Energy* **2012**, *37*, 615–622. [CrossRef]
81. Bradley, T.H.; Moffitt, B.A.; Mavris, D.N.; Parekh, D.E. Development and experimental characterization of a fuel cell powered aircraft. *J. Power Sources* **2007**, *171*, 793–801. [CrossRef]
82. Wurster, R.; Schmidtchen, U. Wasserstoff-Sicherheits-Kompendium. Available online: https://www.dwv-info.de/wp-content/uploads/2015/06/Wasserstoff_kompendium.pdf (accessed on 11 November 2022).
83. Tian, Y.; Zou, Q.; Lin, Z. Hydrogen Leakage Diagnosis for Proton Exchange Membrane Fuel Cell Systems: Methods and Suggestions on Its Application in Fuel Cell Vehicles. *IEEE Access* **2020**, *8*, 224895–224910. [CrossRef]
84. Pacific Northwest National Laboratory. Hydrogen Tools: Hydrogen Compared with Other Fuels. Available online: https://h2tools.org/hydrogen-compared-other-fuels (accessed on 11 November 2022).
85. Lanz, W. Module 7: Fuel Cell Bus Maintenance. Available online: https://www.energy.gov/sites/default/files/2014/03/f12/fcm07r0.pdf (accessed on 11 November 2022).
86. Saxe, M.; Folkesson, A.; Alvfors, P. Energy system analysis of the fuel cell buses operated in the project: Clean Urban Transport for Europe. *Energy* **2008**, *33*, 689–711. [CrossRef]
87. Sathik, M.H.M.; Prasanth, S.; Sasongko, F.; Pou, J. Lifetime estimation of off-the-shelf aerospace power converters. *IEEE Aerosp. Electron. Syst. Mag.* **2018**, *33*, 26–38. [CrossRef]
88. FUMATECH BWT GmbH. Membrane Humidifiers: Fumasep® High Performance Membrane Humidifiers for Fuel Cells. Available online: https://www.fumatech.com/NR/rdonlyres/0B9A1C7F-5BA6-4409-A003-5C4E79CD61AB/0/FUMATECH_BWT_GmbHMembrane_Humidifiers.pdf (accessed on 11 November 2022).
89. Powercell Sweden AB. Datasheet PowerCellution. Available online: https://www.datocms-assets.com/36080/1636022137-power-generation-system-100-v221.pdf (accessed on 11 November 2022).
90. Sun, J.; Wang, F.; Ning, S. Aircraft air conditioning system health state estimation and prediction for predictive maintenance. *Chin. J. Aeronaut.* **2020**, *33*, 947–955. [CrossRef]
91. Freeman, F.; van Kessel, P.; Verhagen, W. Age and Condition-Based Preventive Replacement Timing for Periodic Aircraft Maintenance Checks. In Proceedings of the PHM Society European Conference, Jeju, Republic of Korea, 8–10 September 2021; Volume 6, p. 12. [CrossRef]
92. Miotti, M.; Hofer, J.; Bauer, C. Integrated environmental and economic assessment of current and future fuel cell vehicles. *Int. J. Life Cycle Assess.* **2017**, *22*, 94–110. [CrossRef]
93. Aubry, J.; Steiner, N.Y.; Morando, S.; Zerhouni, N.; Hissel, D. Fault tolerant control of a Proton Exchange Membrane Fuel Cell based on a Modified Failure Mode and Effect Analysis. In Proceedings of the IEEE Vehicle Power and Propulsion Conference (VPPC), Gijon, Spain, 18 November–16 December 2020; pp. 1–5. [CrossRef]

94. Lin, P.; Zhou, P.; Wu, C.W. A high efficient assembly technique for large PEMFC stacks. *J. Power Sources* **2009**, *194*, 381–390. [CrossRef]
95. Rubio, M.A.; Urquia, A.; Dormido, S. Diagnosis of performance degradation phenomena in PEM fuel cells. *Int. J. Hydrogen Energy* **2010**, *35*, 2586–2590. [CrossRef]
96. Rangel, C.M.; Silva, R.A.; Travassos, M.A.; Paiva, T.I.; Fernandes, V.R. Fuel Starvation: Irreversible Degradation Mechanisms in PEM Fuel Cells. In Proceedings of the 18th World Hydrogen Energy Conference 2010—WHEC 2010, Essen, Germany, 16–21 May 2010; Stolten, D.; Grube, T., Eds.; Forschungszentrum IEF-3: Jülich, Germany; Schriften des Forschungszentrums Jülich Reihe Energie & Umwelt: Jülich, Germany, 2010; pp. 31–35.
97. Balogun, E.; Barnett, A.O.; Holdcroft, S. Cathode starvation as an accelerated conditioning procedure for perfluorosulfonic acid ionomer fuel cells. *J. Power Sources Adv.* **2020**, *3*, 100012. [CrossRef]
98. Onanena, R.; Oukhellou, L.; Candusso, D.; Harel, F.; Hissel, D.; Aknin, P. Fuel cells static and dynamic characterizations as tools for the estimation of their ageing time. *Int. J. Hydrogen Energy* **2011**, *36*, 1730–1739. [CrossRef]
99. Depernet, D.; Narjiss, A.; Gustin, F.; Hissel, D.; Péra, M.C. Integration of electrochemical impedance spectroscopy functionality in proton exchange membrane fuel cell power converter. *Int. J. Hydrogen Energy* **2016**, *41*, 5378–5388. [CrossRef]
100. Wu, J.; Yuan, X.Z.; Wang, H.; Blanco, M.; Martin, J.J.; Zhang, J. Diagnostic tools in PEM fuel cell research: Part I Electrochemical techniques. *Int. J. Hydrogen Energy* **2008**, *33*, 1735–1746. [CrossRef]
101. Wu, J.; Yuan, X.Z.; Wang, H.; Blanco, M.; Martin, J.J.; Zhang, J. Diagnostic tools in PEM fuel cell research: Part II Physical/chemical methods. *Int. J. Hydrogen Energy* **2008**, *33*, 1747–1757. [CrossRef]
102. Lin, R.H.; Xi, X.N.; Wang, P.N.; Wu, B.D.; Tian, S.M. Review on hydrogen fuel cell condition monitoring and prediction methods. *Int. J. Hydrogen Energy* **2019**, *44*, 5488–5498. [CrossRef]
103. Geissdoerfer, M.; Vladimirova, D.; Evans, S. Sustainable business model innovation: A review. *J. Clean. Prod.* **2018**, *198*, 401–416. [CrossRef]
104. DaSilva, C.M.; Trkman, P. Business Model: What It Is and What It Is Not. *Long Range Plan.* **2014**, *47*, 379–389. [CrossRef]
105. Zott, C.; Amit, R.; Massa, L. The Business Model: Recent Developments and Future Research. *J. Manag.* **2011**, *37*, 1019–1042. [CrossRef]
106. Osterwalder, A.; Pigneur, Y. *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*; Wiley&Sons: New York, NY, USA, 2010.
107. Osterwalder, A. The Business Model Ontology: A Proposition in a Design Science Approach. Ph.D. Thesis, L'Université de Lausanne, Lausanne, Switzerland, 2004.
108. Al-kaabi, H.; Potter, A.; Naim, M. An outsourcing decision model for airlines' MRO activities. *J. Qual. Maint. Eng.* **2007**, *13*, 217–227. [CrossRef]
109. Randall, C. Airbus & ElringKlinger Launch Fuel Cell Aircraft Partnership. Available online: electrive.com (accessed on 15 October 2020).
110. MTU Aero Engines. Flying Fuel Cell. Available online: https://www.mtu.de/technologies/clean-air-engine/flying-fuel-cell/ (accessed on 11 November 2022).
111. Stropnik, R.; Lotrič, A.; Bernad Montenegro, A.; Sekavčnik, M.; Mori, M. Critical materials in PEMFC systems and a LCA analysis for the potential reduction of environmental impacts with EoL strategies. *Energy Sci. Eng.* **2019**, *7*, 2519–2539. [CrossRef]
112. Amit, R.; Schoemaker, P.J.H. Strategic assets and organizational rent. *Strat. Mgmt. J.* **1993**, *14*, 33–46. [CrossRef]

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