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Experimental Activities on a Hydrogen-Powered Solid Oxide Fuel Cell System and Guidelines for Its Implementation in Aviation and Maritime Sectors

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Abstract: Solid oxide fuel cell (SOFC) systems are spreading worldwide and, for limited applications, also in the transport sector where high power rates are required. In this context, this paper investigates the performance of a six-cell SOFC stack by means of experimental tests at different power levels. The experimental campaign is based on two different stages: the heating phase, useful for leading the system temperature to approximately 750 °C, and the test stage, in which the experimental activities are properly carried out with varying input parameters, such as the DC current load. In addition, a detailed post-processing activity is conducted to investigate the main performance that could be used in the scale-up processes to design and size a SOFC-based system for transportation. The experimental results concern the electrical power, which reaches 165 W, roughly 27 W for each cell and with 52% electrical efficiency, as well as the theoretical thermal power and efficiency, useful for cogeneration processes, with maximum values of 80 W and 25%, respectively, achieved at maximum load. This discussion then shifts to an in-depth analysis of the possible applications of SOFCs in sustainable mobility, particularly in the maritime and aviation industries. The complexities of the issues presented underscore the field's multidisciplinary nature, ranging from materials science to system integration, and environmental science to regulatory standards. The findings presented could be useful to scientists, engineers, policymakers, and industry stakeholders working on the development and commercialization of SOFC systems in the sustainable transportation sectors.

Keywords: hydrogen; solid oxide fuel cell; experimental activity; cogeneration process; sustainability; mobility; aviation and maritime sector

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1. Introduction

The challenges posed by climate change and air pollution have catalyzed the scientific community to embark on a deep energy transition, facilitating the transit from a fossil-fuel-dependent economy to an emerging paradigm [1,2]. The transportation sector assumes a pivotal position within a sustainable and efficient development framework, as it accounts for approximately one-third of energy consumption and nearly a quarter of greenhouse gas emissions only in Europe [3,4]. In this context, hydrogen-powered propulsion systems, including fuel cells, assume a crucial role in advancing a sustainable mobility model.

In the arena of commercialized fuel cell electric vehicles, proton exchange membrane (PEM)-based powertrains represent the current state of the art, garnering significant attention and widespread adoption. PEM-based stacks exhibit notable advancements in power density, ranging from 1.65–3.12 kW L^{-1}, while operating at respectable efficiencies of approximately 40–50% [5,6]. Conventionally, other fuel cell systems, such as the Solid Oxide Fuel Cell (SOFC), were not commonly regarded as suitable for automotive or transportation applications. In recent years, there has been a growing interest in SOFC-based powertrains, which has attracted the attention of the scientific community. SOFC-based propulsion systems offer substantial potential [7,8], presenting various advantages, including: (1) enhanced fuel flexibility, encompassing hydrogen and hydrocarbons such as diesel, biodiesel, and clean coal gas; (2) streamlined fuel processing procedures; (3) greater tolerance to impurities in reactant gases; (4) utilization of less expensive metal catalysts; (5) generation of high-quality thermal output (ranging from 600 to 1000 °C), which can be utilized by other components, systems, or for cogeneration purposes; (6) higher overall conversion efficiencies. These emerging prospects have paved the way for further exploration and development in the field of SOFC-based powertrains.

Initially, SOFCs were primarily viewed as Auxiliary Power Units (APUs) with the potential to replace or greatly reduce the size of batteries in hybrid vehicles. This aimed to enhance vehicle performance and fuel efficiency, while also exploring the possibility of assuming a central role in propulsion systems [9]. Contextually, researchers began directing their attention toward Unmanned Aerial Vehicles (UAVs), where SOFCs could be employed as propulsion systems, particularly in hybrid configurations [10–13]. The interest in hydrogen-powered rail vehicles has been steadily growing, with a particular focus on their potential applications in heavy rail transportation. High-temperature Solid Oxide Fuel Cells are deemed suitable for such use cases [14], while Proton Exchange Membrane (PEM) systems are more favorable for lighter rail vehicles [15–17]. A novel hybrid energy system model, combining SOFCs with a gas turbine (SOFC-GT), was even proposed for long-haul freight locomotives [18], as spatial requirement systems are comparable to current diesel engines. In [19], a simulation was conducted using a system consisting of a 2.8 MW SOFC and a 500 kW GT, which demonstrated the capability to transport 480 tons of freight with a 120-ton locomotive along a specific route at an average speed of 72 km h^{-1}. Additionally, as early as 2010, it was agreed that hybrid locomotives based on SOFC technology could have potentially replaced conventional diesel locomotives [20].

SOFC systems have gained significant attention as leading energy solutions in both stationary generations for various purposes and facilities, as well as propulsion systems for large ships [21,22]. Notably, Bloom Energy, an American fuel cell corporation, has shown particular interest in applying SOFC technology to the maritime sector, particularly in cruise ships. It is projected that, by 2027, over 100 cruise ships will be outfitted with approximately 4000 MW of fuel cells [23,24].

The widespread adoption of Solid Oxide Fuel Cells in automotive applications has been hindered by several limitations inherent to the sector. Factors such as fast start-up and transient response time, as well as device compactness, pose significant challenges. The automotive industry imposes stringent restrictions on space and weight, and any increase in these parameters would have a detrimental effect on vehicle design. In the case of SOFC-based range extenders, AVL List GmbH has established target criteria to ensure competitiveness with existing technologies [25]. These criteria include achieving net system efficiencies greater than 50%, power outputs of at least 15 kW, and volumetric stack power densities ranging from 1 to 1.2 kW per liter. However, despite extensive research efforts focused on optimizing construction geometries, state-of-the-art commercial SOFC stacks typically achieve power densities of only 0.1 to 1 kW per liter [26]. Thus, there is still a gap between the current performance of SOFC stacks and the desired metrics set by the automotive industry. Therefore, in addition to rapid start-up times and minimal degradation rates, efficiency and power density are crucial performance indicators for power generation systems used in the field of mobility. These factors must be carefully considered in order to meet the demanding requirements of over 10,000 h of life time and minimal degradation, which are essential for achieving the economic viability of SOFC technology [25,27,28]. To tackle this challenge, both research and industry are focusing on reducing the operating temperature of SOFCs. Furthermore, the manufacturing process and structural assembly play a critical role in ensuring optimal performance. Many researchers are involved in investigating new materials and processes to enhance properties [29–33]. Particularly, Zhou et al. [34] investigated advances in the material developments for ceramic fuel cells, and Raza et al. [35] presented a novel concept and a material investigation for one-component SOFC systems.

Metal Supported Cells (MSC) have emerged as a promising option for mobile applications due to their excellent mechanical strength and redox stability [25], while major companies rely on Anode Supported Cells (ASC) as their preferred choice. Udomsilp et al. [25] conducted a study showcasing the potential of an innovative morphological and MSC configuration, resulting in a remarkable tenfold increase in power density (reaching 3.13 W cm^{-2} at 1123.15 K and 0.7 V) compared to the existing literature on single-cell performance in industrial settings. Nevertheless, anode-supported cells continue to be a viable option for SOFC-based mobility applications. In this context, emphasis is placed on reducing the thickness of the electrolyte to a few micrometers, as electrode polarization emerges as a dominant factor contributing to overall performance degradation.

To address the issue of high temperatures, alternative materials are being explored as substitutes for the conventional Ni-YSZ structure used in 900–1000 °C-based SOFCs [36]. These alternative materials must be characterized by their favorable mechanical properties, thermo-mechanical expansion coefficients comparable to those of the electrodes, good ionic conductivity, and high resistance to electronic conductivity [37]. Various oxide-based materials have been identified as promising candidates. Notably, Ni-scandia-stabilized zirconia (ScSZ) demonstrates significantly higher ionic conductivity within the temperature range of 650–750 °C, similar to the performance exhibited by gadolinium-doped ceria (CGO)-based structures, as Ni-CGO. The latter is commonly employed in intermediate or low-temperature applications, as seen in the stack designs of Ceres Power [38] and Sunfire [39]. Wehrle et al. [40] presented a comprehensive multiscale modeling approach to assess the direct influence of cell materials and morphologies on the performance of commercial-scale systems. Their findings indicated that the proposed system achieved a stack power density of 1.85 kW L^{-1} and a net system efficiency of 52.2% at an operating temperature of approximately 700 °C. The stack exhibited manageable temperature gradients of less than 14 K cm^{-1}. Importantly, the power density exceeded that of commercial stacks and surpassed the industrial targets set for SOFC-based range extenders. In addition, the paper [40] reported the interest playing around the main powertrain development companies in SOFC-based propulsion; such as: Delphi, Nissan, Volvo, Weichai Power, and AVL List GmbH, along with SOFC stack manufacturers such as Ceres Power and Sunfire. In a separate study, Kerviel et al. [41] developed a dynamic numerical model for a fuel cell electric vehicle utilizing a PEM powertrain. The model incorporated an electric-assisted turbocharger and an electric supercharger in conjunction with a SOFC to extend the vehicle's range. The results demonstrated the suitability of SOFCs for transportation applications, particularly as range extenders. Specifically, a 24-kWh electric vehicle experienced a 252% increase in driving range when aided with a 5 kW SOFC stack. Results indicated a route of more than 600 km with a pure hydrogen tank containing 6.2 kg of fuel.

Extensive experimental research has been conducted to understand and optimize the energy performance of SOFCs. Typical considerations include the type of fuel employed, the operating temperature, the cell design, and the materials. There have been efforts to test SOFCs under various operating conditions in order to comprehend their behavior and enhance their dependability, efficiency, and longevity. Research efforts also extend to stability verification [42–45]. Notably, in a recent publication [45], a study demonstrated the stability of an SOFC stack operating at 0.3 A cm^{-2} for a duration of over 140 h. While there has been a substantial amount of research on the general uses of SOFCs, in-depth and sector-specific assessments have been less common, particularly those focused on the unique constraints and requirements of maritime and aviation applications. The research gap that emerges is the translation of experimental SOFC performance data into real-world maritime and aviation applications. There is a clear need for more in-depth research into how SOFC performance under controlled conditions translates to operational, real-world conditions, which present their own unique challenges and requirements. In the maritime and aviation industries, the specific operational conditions, such as the marine and high-altitude atmospheres, and the unique load requirements due to varying drive cycles, necessitate a thorough understanding of how SOFC systems would perform under such conditions. This includes understanding how these conditions affect the efficiency, durability, and lifetime of SOFCs. In addition, the operational, economic, environmental, regulatory, and technological considerations in these sectors have been largely unexplored. This also includes understanding how SOFC systems can be integrated with existing or potential future infrastructures, evaluating lifecycle costs and environmental impacts, navigating regulatory landscapes, and predicting potential technological advancements.

Within this framework, this article aims to present experimental research on solid oxide fuel cell systems powered by hydrogen, and to provide valuable insights for the development and commercialization of SOFC technologies in the maritime and aviation sectors, thereby contributing to the larger objective of achieving sustainable mobility. The objective is to assess the energy performance of the stack and develop a comprehensive technical-energy map to understand its potential. These experimental activities lay the groundwork for understanding SOFC energy performance and provide the foundation for scaling up these technologies for real-world applications, including the sustainable maritime and aviation transportation sectors. By analyzing and interpreting the results obtained from the experimentation campaign, the study will provide insights into the feasibility of employing this stack in powertrain systems. The discussion then shifts to an in-depth examination of the unique difficulties and potential of SOFC implementation in maritime and aviation applications. The discussion considers the specific environmental conditions, cargo requirements, fuel storage and refueling operations, standards and regulations, and the potential for hybrid systems in both industries. In addition, the analysis includes broader operational, economic, environmental, regulatory, and technological factors that influence the practical application of experimental results.

In this context, the present paper illuminates a path for cross-sector collaboration between scientists, engineers, policymakers, and industry stakeholders by highlighting the multidisciplinary nature of this discipline. This innovative discussion is a significant contribution to the SOFC research community, with the goal of guiding future research and development efforts toward the successful commercialization of SOFCs in sustainable mobility sectors.

2. Materials and Methods

The “materials and method” section outlines the comprehensive approach taken to conduct an experimental campaign on solid oxide fuel cells (SOFC) within specialized test bench facilities. Advanced equipment was utilized to gather accurate data and precisely control the variables during the experiments. Additionally, an extensive literature search was undertaken to gather valuable insights into SOFC-based mobility, which will be presented in subsequent sections. By combining experimental data acquisition and an in-depth literature review, this study attempts to contribute a foundation for evaluating the feasibility and potential of SOFCs in mobility applications.

Experimental tests on a SOFC system are presented. The research presented here is part of a long-term investigation conducted by the authors [46–50].

Subsequently, the paper is enriched by outlining insights into SOFC-based mobility and guidelines for technology diffusion.

3. Layout of the SOFC Test Station

This paragraph illustrates and provides a description of the layout of the SOFC test station.

The main components are reported in the simplified scheme in Figure 1, namely:

- measurement and control instruments; i.e., manometers for measuring pressure, automatic and manual systems for regulating pressure, mass flow controllers for regulating flow rates from the terminal, thermocouples for detecting temperatures in key stations;

- a depot for gas stocks (hydrogen, nitrogen), with a high degree of purity (about 99.99%) and a maximum pressure of 250 bar;
- a working fluid supply and distribution system, managed by a control unit that operates on the numerous valves of the test bench;
- an air volumetric compressor that stores the air in an auxiliary tank at 12 bar, with a two-stage purification system, to eliminate impurities from the air;
- a reforming section for the fuel processing of carbon-based gases, in particular methane, converted into hydrogen-rich gaseous streams;
- a reformate section to prevent steam to condensate;
- a SOFC setup system, the heart of the test bench, which contains the fuel cell stack;
- a furnace, useful for heating the system and maintaining it at the set nominal temperature;
- a control system, for data acquisition, detection/collection, transmission, control, and processing activities;
- a gas exhaust system, which discharges the exhaust gas deriving from the stack;
- a safety system (not shown in Figure 1) made up of the sensors, the gaseous composition control unit, and the hood and forced gas suction system.

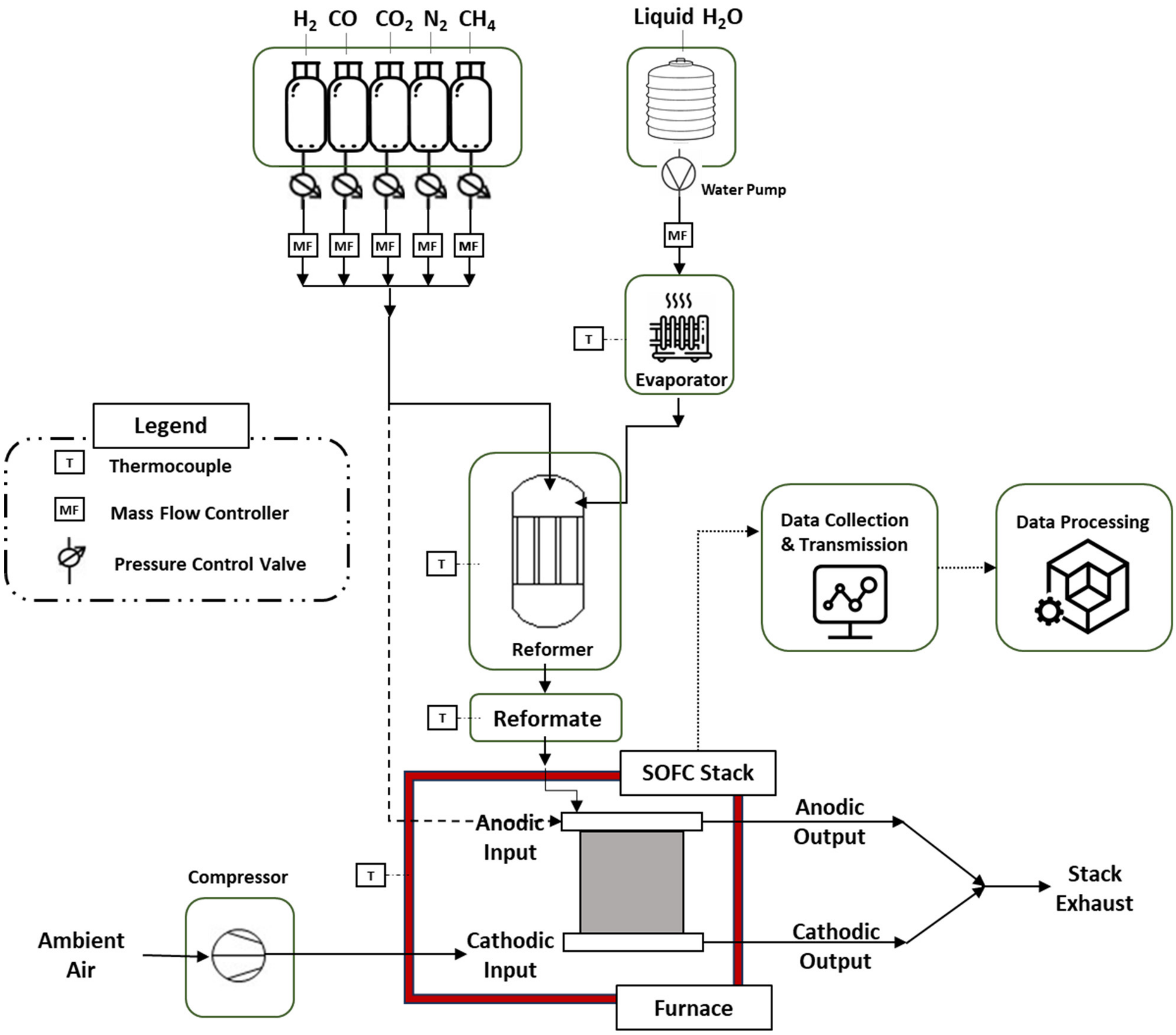

Figure 1. Simplified scheme of the test bench of the Solid Oxide fuel cell stack.

In order to investigate the SOFC system performance, experimental campaigns are carried out, analyzing fluid dynamics, and electrical and thermal variables. Because of the high operative temperature, the experimental tests are divided into two different stages: the heating and test phases.

- The first stage is required to heat the SOFC system, which is led from ambient temperature to approximately 750 °C, the nominal temperature, thanks to the furnace present in the test bench. The input flows, namely hydrogen, air, and nitrogen flows, are maintained constant and the heating is performed with a temperature ramp of 100 °C h^{-1}; therefore, more than 7 h are needed.
- During the test stage, instead, the SOFC system is at the nominal temperature, and the experimental tests are conducted changing the DC load, from the minimum to the maximum current (from 0 A to 33 A) and vice versa but maintaining constant the input flows. The current load step is imposed to 1 A; the current is varied with a time step of 1 min, intending to overcome the SOFC system dynamic oscillations.

Once the experimental tests are conducted, a post-processing phase is performed, analyzing and managing the collected data. Different parameters are calculated, starting from the parameters acquired, which are useful for characterizing the fuel cell system.

Firstly, since the hydrogen flow is imposed constant but the output current is variable, it is important to analyze the utilization factor (U_f) trend, obtained as the ratio of the hydrogen flow that reacts (q_{H2}^{react}) and the input flow (q_{H2}^{in}), as reported in Equation (1). The numerator is calculated, in Equation (2), considering the cell current (I), the cell number (n_c), the standard molar volume of hydrogen (MV_{H2}), and Faraday's constant (F).

$$U_f = \frac{\dot{q}_{H2}^{react}}{\dot{q}_{H2}^{in}} \quad (1)$$

$$\dot{q}_{H2}^{react} = \frac{I \cdot n_c \cdot MV_{H2} \cdot 60}{2\,F} \quad (2)$$

In addition, the main outputs of the system, useful for the final user, are calculated; i.e., the electrical and thermal power and efficiency. The electrical efficiency is calculated as the product of the cell number, voltage, and current (n_c, V_c, and I_c, respectively), as reported in Equation (3). The efficiency, instead, as shown in Equation (4), is the ratio between the electric power and the product of the low heating value (LHV_{H2}), expressed by J Nl^{-1}, and the hydrogen flow as input.

$$P_{el} = n_c\, V_c\, I_c \quad (3)$$

$$\eta_{el} = \frac{P_{el}}{\frac{\dot{q}_{H2}^{in}}{60}\, LHV_{H2}} \quad (4)$$

Regarding the thermal performance, theoretical values are calculated, since the real value strictly depends on cogeneration process demand, which is not possible to consider in the considered test bench. The theoretical thermal power is calculated via Equation (5), considering the difference between the thermoneutral and the cell voltage (V_{tn} and V_c, respectively). Furthermore, in this case, the theoretical thermal efficiency is determined as the ratio of thermal power and the product of low heating value and hydrogen flow as input (Equation (6)).

$$P_{th} = n_c\, I_c\, (V_{tn} - V_c) \quad (5)$$

$$\eta_{el} = \frac{P_{th}}{\frac{\dot{q}_{H2}^{react}}{60}\, LHV_{H2}} \quad (6)$$

In the equations, U_f, $\dot{q}_{H2}^{react}$, P_{el}, P_{th}, η_{el} have the following units of measure: adimensional, NL min^{-1}, W, W, adimensional.

Active surface and material properties, such as electrolytes and electrodes of the fuel cell element, are shown in Table 1.

Table 1. SOFC cell properties.

Fuel Cell Active Area\cm^2	80
Anode	Ni/YSZ
Electrolyte	8YSZ
Cathode	(La,Sr)(Co,Fe)O_3/Gd_2O_3-CeO_2

4. Results

Following the experimental test scheduling, the main performance of the solid oxide fuel cell system, achieved at the described test bench, is monitored and recorded and the main findings are reported.

Before starting with the performance test, a heating phase is performed, and the SOFC system behavior is shown in Figure 2. The heating phase is 8 h long and all the main thermocouples, present in the system, demonstrate the heating phase conclusion. Six different temperature trends are shown, which regard: the inlet air and cathodic exhaust temperature (Figure 2a), the inlet fuel and anodic exhaust temperature (Figure 2b), and the top and bottom stack temperature (Figure 2c). The whole stack is homogeneously heated and follows a similar trend. A slight difference is present between the top and bottom center of the stack, which can differ by a maximum of 75 °C, but can reach a final temperature of about 750 °C anyway. It should be underlined that the inlet flow of hydrogen, nitrogen, and air is maintained constant during the entire heating process, with values of 0.6 Nl min^{-1}, 1.8 Nl min^{-1}, and 6 Nl min^{-1} respectively (Figure 2d).

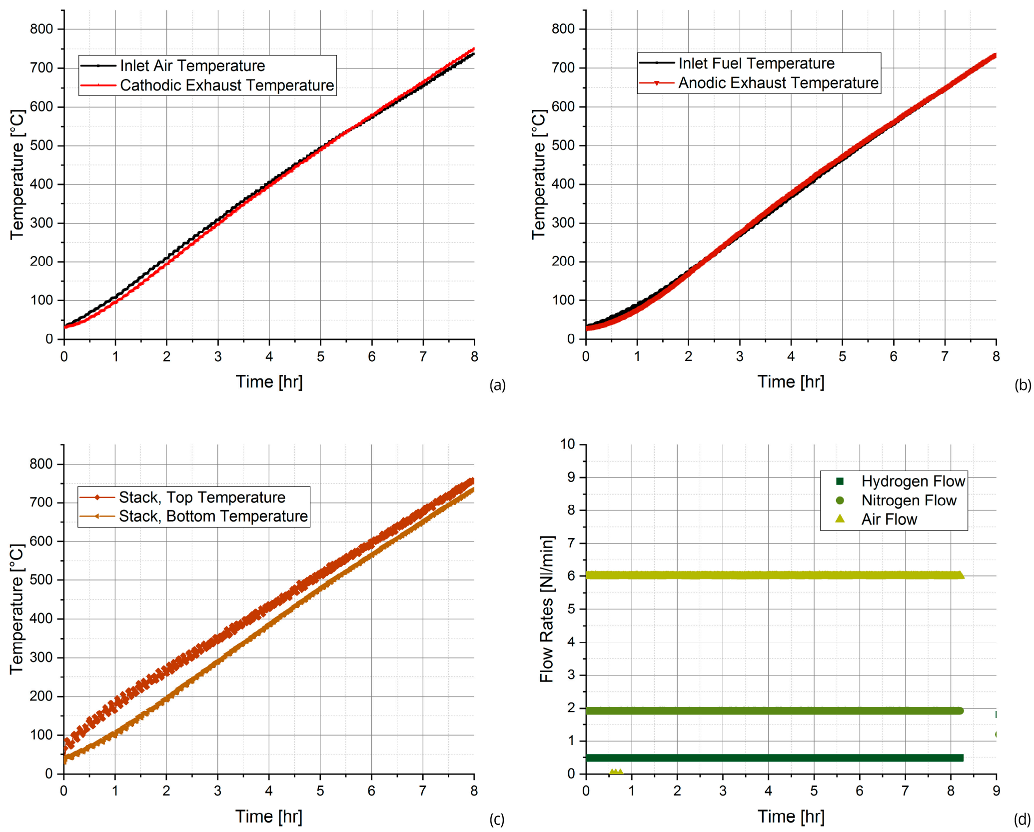

Figure 2. Performance of the SOFC system during the heating phase: (**a**) Cathode side temperatures; (**b**) Anode side temperature; (**c**) Top and bottom temperature; (**d**) Mass flow rate of the main inputs.

When the heating phase has been concluded and the SOFC system has reached the nominal temperature of approximately 750 °C, the test phase is performed. The experimental tests are approximately 75 min long, divided into two sections, with an increasing and a decreasing load trend. In detail, as shown in Figure 3a, in the first section, the electronic load is controlled to vary its current from 0 A to 33 A; while, in the second phase, an inverse trend is imposed, with a decreasing load current rate, from 33 A to 0 A (Figure 3a). Another controlled variable is the hydrogen flow as input (Figure 3b), which is maintained constant at the nominal value of 1.8 Nl min^{-1}. For these reasons, the utilization factor, achieved as Equation (1), follows the load current trend; it ranges from 0% at 0 A to 76% at the maximum current tested.

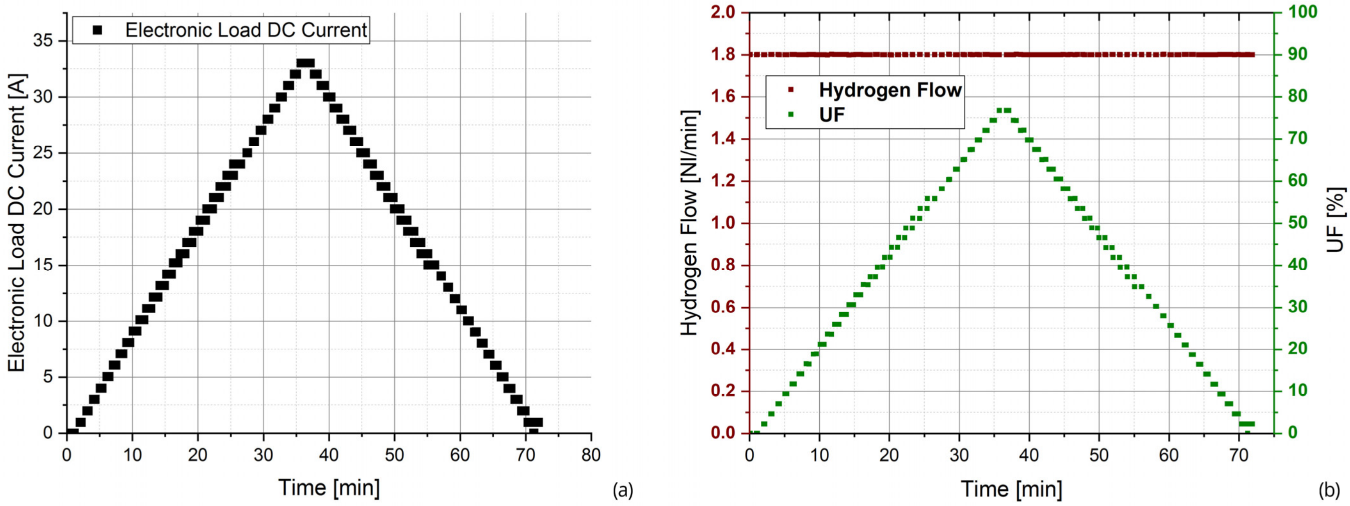

Figure 3. Performance of the SOFC system during the test phase: (**a**) Electronic Load DC current; (**b**) Hydrogen flow and utilization factor.

Regarding the temperature variables shown in Figure 4, their trends are rather constant. The effect of the load variation is almost negligible, causing only small variations. As shown in Figure 4a, in the cathodic chamber, the outlet temperature of the exhaust gas assumes higher values compared to the inlet one, owing to the chemical reaction occurring, with a mean value of 775 °C and 745 °C, respectively. Even the input and output temperature of the anodic chamber (Figure 4b) can be considered constant, assuming a mean value of 750 °C and 764 °C, with narrow variations. The outlet flow temperature of the anode is lower than the cathode one, mainly due to the nitrogen dilution (40% in volume) of the anodic flow, which does not take part in the reaction, being inert.

Even the bottom and top temperature levels of the stack are constant, as illustrated in Figure 4c, with higher values for the top section (around 775 °C) compared to the bottom one (approximately 753 °C), owing to the higher convective and radiative heat exchange in the upper part of the stack, given the physical structure of the furnace.

Regarding the cell voltage in Figure 4d, the voltage trends of the six cells of the SOFC stack are depicted and they do not present significant differences between them, showing the proper behavior of the stack. The voltage levels vary between 1.18 V, which represents the open-circuit voltage, and 0.81 V at the maximum tested current (33 A).

Once the electrical and thermal parameters are shown, it is possible to analyze the main outputs of the SOFC system, the ones useful for the final user, namely electrical and thermal powers and efficiencies. Figure 5a shows the electrical power (the blue line) and the electrical efficiency (the green line), which follow the DC trend, since the current variation is more relevant than the voltage one. The SOFC system reaches approximately 165 W, i.e., roughly 27 W for each cell, with 52% of electrical efficiency at maximum load. For the same reason, the theoretical thermal power and efficiency shown in Figure 5b follow the load variations, owing to Equations (5) and (6). The achieved values are lower than the electrical ones, with a maximum value of 80 W of theoretical thermal power (blue line in Figure 5b) and 25% of theoretical thermal efficiency (green line in Figure 5b), both obtained at maximum load.

These parameters are also plotted as a function of the current (Figure 5c,d), reporting the DC load on the x-axis. As expected, the obtained values at the same current are similar in the two DC load phases, namely at increasing and decreasing current tests. In addition, the polarization curve assumes the standard trend, obtaining a stack voltage between 7 V and 4.9 V.

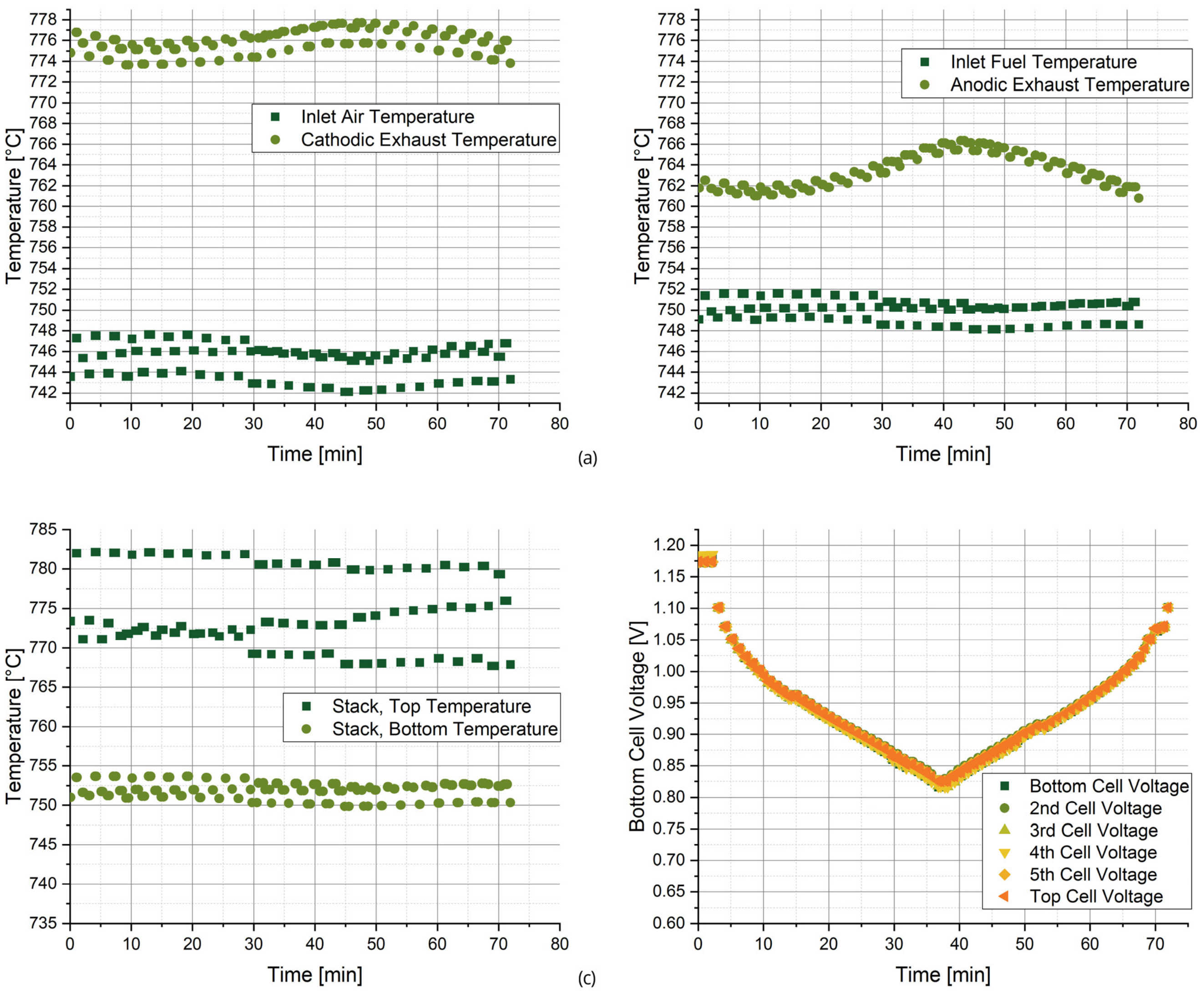

Figure 4. Performance of the SOFC system during the test phase: (**a**) Cathode side temperatures; (**b**) Anode side temperature; (**c**) Top and bottom temperature; (**d**) Voltage of the six cells composing the stack.

This scientific article aims to explore the significance of experimental activities conducted on solid oxide fuel cell stacks within testbench facilities. It emphasizes the critical role of testbench facilities in providing a controlled environment for performance evaluation and future eventual optimization by managing control parameters or even SOFC stack geometry or manufacturing. The findings obtained from this experimental approach serve to understand how guidelines can guide future modifications and evolutions of SOFCs, and pave the way for the possible adoption and effective deployment of SOFCs in propulsion applications, contributing to the advancement of sustainable and efficient transportation technologies. To fulfill this objective, the forthcoming sections of this article will specifically focus on two aspects. The first section will delve into "Insights for SOFC applications in sustainable mobility", exploring the potential of SOFCs in driving sustainable transportation. The second section will provide contextual guidelines for scaling up the SOFC systems, offering valuable recommendations for the successful expansion and implementation of these technologies.

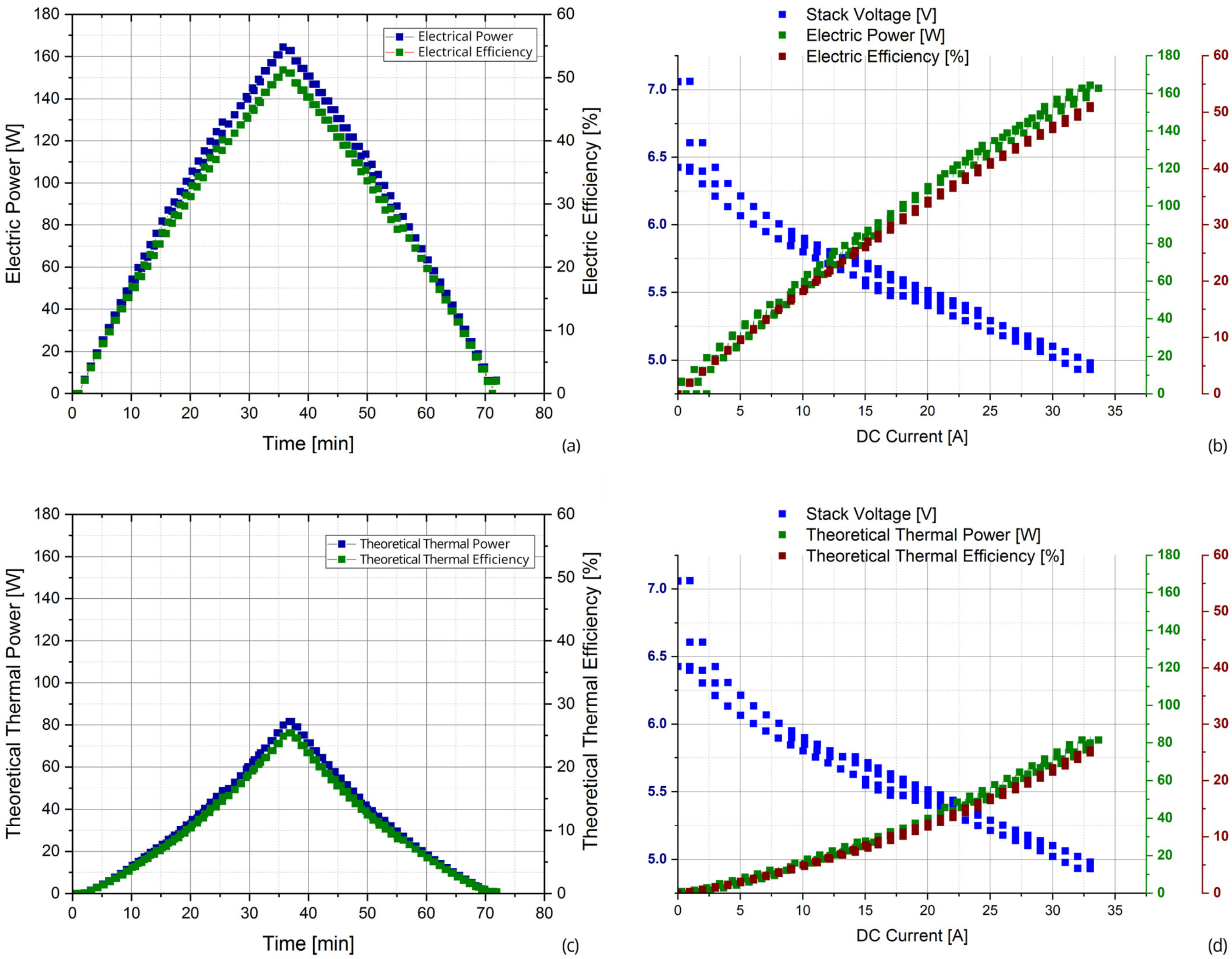

Figure 5. Performance of the SOFC system during the test phase: (**a**) Electric power and efficiency; (**d**) Thermal power and efficiency; (**c**) Polarization curve with electrical performance; (**d**) Polarization curve with thermal performance.

5. Insights for SOFC Applications in Sustainable Mobility

The use of solid oxide fuel cells (SOFCs) is an innovative approach to attaining sustainable mobility [51]. SOFCs have the potential to play a significant role in minimizing greenhouse gas emissions across multiple modes of transportation [52–54], by converting chemical energy directly into electricity through a highly efficient electrochemical process. SOFCs are distinguished by their use of a ceramic solid oxide electrolyte. They operate at high temperatures, as discussed above, which provides a number of advantages, such as the ability to use a variety of fuels [55] and high electrical efficiencies [37,56]. In addition, the high-quality waste heat produced by SOFCs can be utilized further, resulting in overall energy efficiencies that can exceed 80% in certain configurations.

SOFC applications, in the context of sustainable mobility, span the road, maritime, and aviation sectors [57]. They offer a potentially more energy-dense alternative to battery electric systems for use in passenger vehicles, buses, and lorries. SOFCs can provide both propulsion and stationary electricity for onboard systems in the maritime industry. Due to their relatively slow speed and extended travel periods, ships are ideally suited for SOFCs because of their high efficiency and ability to utilize widely available fuels. SOFCs are being studied as a potential solution for auxiliary power units and, in the distant future, propulsion power in the aviation industry, despite the fact that their development is still in its infancy.

However, obstacles persist, such as durability, the need to operate at high temperatures, and system complexity. Additionally, regulations and standards, as well as the development of a suitable refueling infrastructure, are essential for the widespread adoption of SOFC technologies. This section aims to provide insights into these challenges, since despite these obstacles, SOFCs present an enticing path to obtaining sustainable mobility. They have the potential to convert transportation systems into more environmentally-friendly, energy-efficient, and sustainable modes with continued research and technological advancement.

5.1. Automotive Sector

The employment of fuel cell technology in this sector is one of the most immediate and significant. Toyota and Hyundai, for example, have already started integrating hydrogen fuel cell technology into their cars, the Mirai and Nexo, respectively [58]. However, Proton-Exchange Membrane Fuel Cells (PEMFCs) are largely used in these [59]. Due to space and heat management issues, SOFCs, with their high operating temperatures, are typically not recommended for automobiles [60]. However, the great efficiency of SOFCs can make them an attractive choice for future heavy-duty mobility [7,61,62], if cost-reduction efforts are successful and safety concerns are addressed.

5.2. Maritime Sector

Compared to other types of fuel cells, SOFCs have a high electrical efficiency of about 50%, a high fuel-to-electricity efficiency, and the capacity to use a wide range of fuels. The use of SOFCs in large ships [63], where size and heat management are less of an issue than in cars, is possible, although PEM fuel cells are still being investigated for such applications [64,65]. SOFCs are a practical choice for zero-emission sea transportation because of their great electrical efficiency and fuel adaptability. Due to their great efficiency, SOFCs are a desirable choice for lowering the maritime sector's carbon footprint [66,67], which currently accounts for 2% of global greenhouse gas emissions [68]. Electric motors for propulsion might be powered by the electrical energy produced by the SOFCs. SOFCs could also be utilized to power stationary systems such as lighting, heating, air conditioning, and different electronic systems that are present on board ships [69]. Internal combustion engine generators, which are typically employed for this purpose, are less effective and more polluting.

5.2.1. Technical Challenges

Current state-of-the-art analysis has reported that, on average, SOFCs present a power density of 0.4–0.6 W cm^{-2} [37]. Higher power densities of up to 2 W cm^{-2} have been reported for solid oxide single cells in the recent literature [70,71]. Depending on the size of the ship and its power requirements, the actual power output for a marine SOFC system might vary, although, for bigger ships, the system could range from several hundred kilowatts to a few megawatts. In order to integrate SOFCs in a naval setting, extra systems for fuel processing [72], heat management, and power electronics must be taken into account. For instance, if natural gas were to be used as fuel, a reformer would be required to transform it into a hydrogen-rich gas suitable for the SOFC. If a generic hydro-carbon is supplied to an external reformer or directly to the SOFC system, the following reactions will take place:

$$C_nH_m + n{\cdot}H_2O \leftrightarrow n{\cdot}CO + \left(\frac{m}{2} + n\right)H_2 \quad (7)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (8)$$

On the anodic side, both hydrogen and carbon monoxide will react, producing water steam and carbon monoxide:

$$H_2 + O^{=} \rightarrow H_2O + 2e^- \tag{9}$$

$$CO + O^{=} \rightarrow CO_2 + 2e^- \tag{10}$$

The cathodic reaction will remain the same:

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{=} \tag{11}$$

The efficiency of the entire system can be improved by using heat produced by the SOFC to power a steam turbine for additional power (in a combined cycle design). Power electronics are required to transform and condition the SOFC-generated electricity so that it is compatible with the ship's electrical systems. Concerning lifetime and resilience, due to their solid-state construction, SOFCs typically have good longevity, although repeated heating and cooling can weaken the materials used to make the cells. Due to their high operating temperatures, SOFCs are less suitable for applications needing frequent start-stop cycles because it can take several hours for them to establish steady-state functioning [73]. As a result, they are better suited for longer journeys where the fuel cell can endure extended durations of working temperature. Table 2 summarizes the pros and cons of SOFC technology in maritime applications.

Table 2. Advantages and disadvantages of SOFC application in the maritime sector.

Pros	Cons and Restrictions
• High Efficiency: SOFCs have a high electrical efficiency of about 50%, and in CHP operation, the efficiency can reach beyond 80%. • Fuel Flexibility: In contrast to other types of fuel cells, SOFCs are capable of using a range of fuels, such as hydrogen, methane, and other hydrocarbons.	• High Operating Temperatures: the SOFCs' high operating temperatures have both benefits and drawbacks. High efficiencies and fuel flexibility are made possible, but problems with materials and durability result as well. The materials may be subjected to heat stress and degradation, which could reduce the cell's lifetime [74]. • Slow Start-Up Times: Due to the high operating temperatures, fast start-up times can be problematic in applications where a speedy start-up is required. • Marine conditions: humidity, salinity, and temperature fluctuations. • Currently, SOFCs are more expensive than conventional power production technologies in terms of cost. As technology advances and economies of scale are obtained, costs could, nevertheless, decrease.

Even though SOFCs have a lot of potential for the maritime industry, additional research and development are required to address issues including high operating temperatures, slow startup times, size and weight, and cost. Moreover, solid oxide fuel cells (SOFCs) face unique difficulties when operating and holding up in marine conditions. The key issues are the variations in temperature, salinity, and humidity that are typical of coastal environments:

- Humidity: SOFC performance can be impacted by high humidity in two different ways. The fuel and oxidant gases may be diluted by the water vapor, which may result in a drop in performance. Second, too much moisture can result in the fuel cell becoming liquid water, which can cause flooding and obstruct the flow of gases. However, compared to fuel cells that operate at lower temperatures, such as PEM fuel cells, the effects of humidity are typically less noticeable with SOFCs due to their high working temperatures [75].

- Salinity: Marine air's high salinity can cause corrosion problems. The fuel cell could malfunction if salt deposits on its components and interacts with the materials, causing corrosion. These effects can be lessened by choosing the right materials and applying protective coatings.
- Temperature Fluctuations: The maritime environment is subject to severe temperature changes, ranging from extremely cold temperatures in northern regions to high temperatures in tropical places. The thermal management system and the fuel cell's functionality may be impacted by these temperature fluctuations. Additionally, due to variations in thermal expansion, thermal cycling (heating up and cooling down) can cause mechanical stresses in the SOFC materials, perhaps resulting in degradation and failure.

In light of these elements, the design of SOFC systems for maritime applications must consider the unique difficulties of the marine environment. Protective coatings to prevent corrosion, thermal management systems to handle temperature changes, and careful system design to control the impacts of humidity can all fall under this category.

5.2.2. Fuel Storage, Regulations, and Refueling Procedure

When contemplating the use of Solid Oxide Fuel Cells (SOFCs) in the maritime industry, standards and regulations are crucial. International standards are established by the International Maritime Organization (IMO) for the performance of international shipping in terms of safety, security, and the environment [76]. These rules would have to be followed by SOFC systems, especially those that deal with safety and pollution. As of today, there are no specific rules concerning SOFCs on ships [77]. However, the IMO is aiming to reduce GHG emissions from ships [78], so more attention will likely be paid to cleaner technology such as SOFCs.

Another important topic is the need for fuel storage, which will vary depending on the kind of fuel being used [79]. If utilized as a fuel, hydrogen can be kept on board in either compressed or liquid form. While liquid hydrogen must be stored at extremely low temperatures (about −253 °C), compressed hydrogen needs high-pressure tanks (usually over 700 bar). There are distinct safety concerns for both types of storage that must be taken into account [80]. For instance, because hydrogen is very flammable and can react with air to generate explosive mixtures [81], the storage system must be built to prevent leaks and must include safety features to deal with any leaks that do happen [82]. To maintain safety, explosion-proof electrical systems and hydrogen sensors may be required [83,84]. It is possible to store another fuel, such as natural gas, as either compressed natural gas (CNG) or liquefied natural gas (LNG). LNG is kept in thermally insulated tanks at low temperatures (around −162 °C). Natural gas is combustible, much like hydrogen, thus safety precautions must be taken to stop and handle leaks. It is important to note that because SOFCs operate at high temperatures, the fuel-reforming process to turn hydrocarbons (such as methane from natural gas) into hydrogen can be internally carried out. This has the benefit of simplifying the fuel infrastructure. Ammonia is also becoming a deeply investigated topic by the scientific community [85–87].

Depending on the fuel being utilized, refueling procedures for Solid Oxide Fuel Cells (SOFCs) employed in maritime applications will change. In the case of hydrogen, refueling entails either moving compressed hydrogen from a storage location to the ship's high-pressure tanks or, in the case of liquid hydrogen, moving the cryogenic liquid to thermally insulated tanks. Although there are currently just a few hydrogen refueling stations in ports, there are continuing initiatives to expand their number. The infrastructure for maritime hydrogen refueling is still fairly limited. It is also important to note that creating hydrogen can be difficult, particularly if using renewable energy is the intended "sustainable path". Compressed natural gas (CNG) or liquefied natural gas (LNG) are transferred to the appropriate storage tanks onboard the ship during refueling if natural gas is utilized. Particularly at ports that service LNG-powered ships, the infrastructure for natural gas refueling is more advanced than that for hydrogen. Refueling procedures for both hydrogen and natural gas must be meticulously executed to avoid leaks and guarantee safety [88,89]. This entails adhering to established safety procedures and utilizing the proper apparatus that can withstand the high pressures or low temperatures present. Additionally, fuelling a ship with a maritime SOFC system can take longer than refilling a ship with a conventional diesel engine. This is particularly true for hydrogen, where high-pressure or cryogenic storage techniques might make refilling more challenging [90]. There is a need for more infrastructure, better safety procedures, and technology advancements to streamline and speed up the refueling process in order to optimize refueling operations for marine SOFC systems.

5.2.3. Drive-Cycle Requests and Features

Depending on the particular use case, a marine vessel's driving cycle can differ depending on whether it is a boat, ship, or ferry. Some ships, especially cargo ships, may travel across open waters in reasonably stable conditions for extended periods of time. Some vehicles, such as ferries, may have a driving cycle with frequent speed variations as they stop and start at different ports. Table 3 summarizes the main features that characterize the drive-cycle of marine vehicles. The required power can achieve values up to 50 MW, and the payload can vary according to the type of vehicles.

Table 3. Drive cycle features for the maritime sector.

Features	Maritime
Power required	<10 kW–50 MW [91]
Average payload	3000 Passengers [92]
Driving range	<1200 km [93]
Current main propulsion	Diesel, methane, LNG [94]

Because they operate at high temperatures, SOFCs have comparatively slow dynamic reaction times. They are unable to swiftly alter their power output to meet sudden variations in load demand as a result. As a result, a hybrid system would probably be required in applications where the load demand frequently and quickly fluctuates, such as on a ferry.

In a hybrid system, the SOFC is often used in conjunction with an energy storage device, such as a battery or supercapacitor [95], or with a coupled energy system, such as gas turbines [96] or internal combustion engines [97]. With a constant power output, the SOFC runs in a largely stable state. In order to adapt to fluctuations in load demand, the parallel energy system can quickly provide the required amount of power. The parallel energy system can operate at times of high power demand to help the SOFC's production. The extra power generated by the SOFC can be used to refuel the energy storage system during times when there is less demand for electricity. A hybrid system can boost the SOFC's general efficiency and longevity in addition to offering a quick reaction to variations in load demand. The SOFC can function at peak efficiency and avoid damage brought on by thermal cycling by being operated in a steady state [98].

5.3. Aviation SECTOR

The application of SOFC technology for aircraft propulsion is still in its early stages in the aviation industry [99,100]. Due to several special difficulties, the use of SOFCs in aviation is not as advanced as in ground transportation or stationary power generation, although it does have potential in specific applications [101,102]. For instance, Airbus has expressed interest in investigating hydrogen as a potential fuel for upcoming aircraft [103,104]. APUs in airplanes could make use of the high energy density of hydrogen and the high efficiency of SOFCs [105].

5.3.1. Technical Challenges

In terms of applications, the use of SOFCs for main propulsion in aircraft is still an active area of study [106] and confronts formidable obstacles because of problems with weight, size, and dynamic response. Auxiliary power units (APUs), which power onboard systems when the main engines are not working, may nevertheless employ SOFCs [105]. Emissions can be decreased and system efficiency increased by using SOFCs for APUs. Table 4 summarizes the pros and cons of SOFC technology in aviation applications.

Table 4. Advantages and disadvantages of SOFC application in the aviation sector.

Pros	Cons and Restrictions
• Efficiency: SOFCs have electrical efficiencies of 50% and can achieve total system efficiencies of over 80% when integrated with a combined heat and power system. This may lower the amount of fuel used. • Emissions: When compared to traditional jet engines, SOFCs emit less pollution. The only byproduct of using hydrogen as a fuel is water, which can help to lessen the carbon footprint of air travel. • Auxiliary Power: SOFCs might be utilized to supply auxiliary power for onboard systems, lessening the strain on the primary engines and enhancing system efficiency in general.	• Dynamic Response: SOFCs are less suited to situations where power demand quickly fluctuates, such as during takeoff and landing, because they have shorter response times as a result of their high working temperatures. • Operating Circumstances: SOFC operation is complicated by the challenging aviation operating circumstances, which include high altitudes and chilly temperatures. To regulate heat and provide air compression, additional systems can be required. • Safety: Hydrogen, a common fuel for SOFCs, is very flammable and can create explosive combinations in the atmosphere. Safety mechanisms are therefore essential, especially in the restricted space of an aircraft.

In the world of aviation, size and weight are crucial limitations because every additional pound or cubic inch can have a big influence on fuel economy and passenger space. Due to the requirement for fuel processing machinery and thermal management systems, traditional SOFC systems must be carefully designed for such applications. Moreover, as previously reported, SOFCs typically run between 700 and 1000 °C. It can be difficult to control these high temperatures in an airplane environment. For the protection of other aircraft systems and to stop heat loss, thermal insulation is necessary. Furthermore, cooling systems are necessary to control heat during times of high load and to cool the system when it is not in use.

In terms of durability, SOFCs must withstand challenging aviation working circumstances, such as vibration, quick temperature and pressure changes, and potentially long periods of inactivity. Air pressure is substantially lower at high elevations than it is at sea level, where aircraft frequently fly. Less oxygen is available for the cathode reaction in the SOFC as a result of the reduced air pressure. As a result, in high-altitude conditions, additional air compression devices could be required to supply adequate oxygen for the SOFC to efficiently operate. The ambient temperature fluctuates with altitude and can go from very high temperatures at cruising altitudes to very low temperatures experienced during takeoff from hot places. The thermal management of SOFC systems [107], which must maintain a constant operating temperature for maximum performance, may face difficulties as a result of this temperature variation. Moreover, while in flight, aircraft experience tremendous vibration. Under situations of extreme vibration, the ceramic materials employed in SOFCs may be brittle and subject to mechanical failures.

Innovative engineering and materials science solutions are needed for each of these issues [108]. Research is still being carried out to create SOFC systems that are lighter, more portable, more robust, and better suited to the unique needs of aviation.

5.3.2. Fuel Storage, Regulations, and Refueling Procedure

Any new technology, including SOFCs in aviation, must be adopted in accordance with standards and regulations. The Federal Aviation Administration (FAA) in the United States [109] and the European Union Aviation Safety Agency (EASA) in Europe [110] have created strict safety and performance standards that must be met by any system deployed in an aircraft, and they may also apply to SOFC systems.

Additional requirements and standards apply to fuel storage. The two principal fuel alternatives for SOFCs have the following key considerations. Storage of hydrogen on board an aircraft is quite difficult [111]. Since hydrogen is less dense than conventional aviation fuels, it needs to be stored at high pressure or in a cryogenic environment to have a reasonable energy density. The decision to use liquid or gaseous hydrogen in an aviation context is heavily influenced by the application's specific requirements, such as weight, space, safety, and refueling infrastructure. While cryogenic storage includes keeping hydrogen as a liquid at temperatures below −253 °C, high-pressure storage entails keeping hydrogen gas at pressures of up to 700 bar. Both approaches would have to adhere to strict safety requirements because they have substantial safety concerns. These would include operating guidelines for preventing and addressing leaks as well as requirements for the design and construction of the storage tanks. The infrastructure and practices for refueling can be significantly impacted by changes in fuel type, so these aspects would also need to be controlled to assure safety and compatibility with current systems. If the SOFC system is hydrogen-powered, the refueling procedure could be comparable to that used for hydrogen fuel cell vehicles today [88]. This process can be comparable to refueling a gasoline or diesel automobile. However, infrastructure for hydrogen refueling is not widely available at present [112], and substantial investment would be necessary to equip airports with this capability. In addition, the high-pressure or cryogenic conditions necessary for hydrogen storage present safety and technical challenges that must be addressed [113].

Due to its high energy density and the fact that it only emits water when utilized in a fuel cell, hydrogen has been frequently explored as a fuel for SOFCs. The low density of hydrogen, however, makes it difficult to store on an aircraft and necessitates either high-pressure or cryogenic storage solutions. As an alternative, hydrogen might be created aboard by reforming hydrocarbon fuels such as jet fuel. This would work better with the current infrastructure for aviation fuel. Refueling operations for an aviation application employing a Solid Oxide Fuel Cell (SOFC) system would heavily depend on the type of fuel used by the SOFC. If the SOFC system uses hydrocarbon fuels such as jet fuel or natural gas, existing airport fueling infrastructure could be used for refueling. The liquid fuel would be poured into the aircraft's fuel tanks, similar to how modern aircraft are refueled. In the aircraft's onboard reformer, hydrocarbon fuel would be converted to hydrogen for use in the SOFC. However, this reforming process can result in carbon dioxide and other pollutant emissions, which could partially offset the SOFC's environmental benefits.

Generally speaking, refueling operations for an aircraft using a SOFC system must adhere to stringent safety standards regardless of the type of fuel used. These would include procedures for connecting and disconnecting refueling equipment, checking for leaks, and ensuring the fuel is correctly and safely loaded onto the aircraft.

5.3.3. Drive-Cycle Requests and Features

In the aviation industry, vehicles can serve different purposes and several mission profiles, depending on the vehicle's market segment and on the requirements of the flight companies, for national or international flights. Table 5 summarizes the average features of such vehicles, including the required power levels, the average payload, and the driving range.

Table 5. Drive cycle features for the aviation sector.

Features	Aviation
Power required	<10 kW–30 MW [114]
Average Payload	1000 Passengers [114,115]
Driving range	<11,000 km [115]
Current main propulsion	Kerosene [94]

The "drive cycle" or mission profile of aircraft can be particularly demanding for energy systems. It consists of a series of phases, each with distinct power requirements:

- Taxi: low-power operation, ground movement of an aircraft
- Takeoff: requires the most power to lift the aircraft off the ground

- Climb: demanding a lot of power to reach cruising altitude
- Cruise: moderate, constant power demand for maintaining altitude and speed
- Descent and landing: low power demand, altitude reduction, and landing preparation
- Taxi: return to low-power operation

Therefore, it is clear that, in the course of a typical flight, an aircraft will encounter periods of high power requirements (such as during takeoff and ascending), followed by periods of more steady power requirements (such as while cruising), and periods of low power requirements (such as during descent and landing). It is difficult for SOFCs to handle these rapidly changing power requirements because of their high operating temperature and slow response times to variations in power demand. Therefore, a SOFC alone may struggle to meet the rapidly changing power requirements of an aircraft's drive cycle, especially during takeoff and climb when power demand is at its peak.

For this reason, numerous researchers and developers have proposed combining SOFCs with systems in a hybrid configuration [116,117]. In such a system, the SOFC would have a near-constant power output, supplying energy for cruise. With their quick response times, other energy systems could provide the additional power needed during takeoff and climb [114,118–120]. In such a configuration, the SOFC system could be sized to meet the flight's average power demand rather than its peak power demand, thereby reducing system weight and potentially enhancing overall efficiency.

6. Guidelines for SOFC System Scale-Up

Scaling up experimental data on SOFC performance for maritime and aviation applications is a multifaceted challenge that necessitates consideration of the sector-specific operating conditions and requirements. The experimental data provided in this paper are a promising foundation, but translating this into real-world applications requires taking into account a number of crucial factors. The long-term durability of SOFC systems under real-world operating conditions is a crucial factor that must be considered in a scale-up procedure [121,122]. SOFCs typically operate at high temperatures, which can eventually lead to thermal stress and degradation [123]. In addition, cyclic loading, which is characterized by frequent changes in power demand, can result in mechanical stress and accelerated wear. Given the variable power requirements of these applications and the challenging environmental conditions they may face, both of these factors may be significant in the maritime and aviation sectors.

Scaling up in the maritime industry must take into account the durability of SOFCs under marine conditions, including potential issues such as saltwater corrosion. Given the power requirements of ships and the variable load during a typical marine drive cycle, a hybrid SOFC system could be a viable option for ensuring dependable performance and efficiency. Thus, the process for scaling up must account for the incorporation of such hybrid systems. SOFC systems could provide propulsion [124] and auxiliary power [125] for a variety of vessel types in the maritime industry. Large vessels, such as cargo ships, that operate for extended periods at a relatively constant speed, could greatly benefit from the high efficiency of SOFCs. However, these vessels also pose unique difficulties. Vibrations and movement on ships, for instance, could potentially affect the SOFC system's mechanical stability. In addition, the fuel choice for SOFCs, which will likely be hydrogen or hydrocarbon fuel, will necessitate storage systems that are compatible with marine safety standards, which are stringent due to the potential dangers at sea. Additionally, the integration of SOFCs with existing ship systems would have to be carefully managed. The integration of SOFCs into ships' complex electrical and thermal systems would require careful system design to ensure compatibility. For instance, the waste heat from SOFCs could potentially be used to heat ships or power thermally activated cooling systems, thereby enhancing the overall system efficiency [126].

When scaling up results in the aviation industry, it is important to consider the unique atmospheric conditions at high altitudes. The lower ambient pressure and temperature fluctuations can have an effect on the performance and durability of SOFCs. Moreover, the high power requirements during the takeoff and climb phases suggest that, similar to the maritime industry, a hybrid system may be the optimal solution for this application. The primary initial application of SOFCs in the aviation industry will likely be in auxiliary power units (APUs) that provide power to on-board systems when the main engines are not running. This application could serve as a valuable stepping stone toward more ambitious objectives, such as the use of SOFCs for propulsion power. However, the integration of SOFC systems into aircraft will require careful design to minimize weight and volume, as each additional kilogram carried by aircraft can have a significant effect on its fuel consumption and operating costs. Given the strong push for zero-emission technologies in the aviation industry, it is likely that SOFCs would be hydrogen-powered. Due to the need to store large quantities of fuel in a very small space while adhering to stringent safety standards, the storage of hydrogen on aircraft presents unique challenges. As previously stated, the choice between liquid and gaseous hydrogen storage will have a substantial effect on the overall design and operation of the SOFC system.

Scaling up the experimental SOFC results to real-world maritime and aviation applications will require a thoughtful and multidisciplinary approach that takes into account not only the performance of the SOFCs themselves, but also the integration with other system components, the operating conditions they will face, and the regulatory environment they will need to navigate. This will be the primary focus of ongoing research and development initiatives. When considering refueling operations and hydrogen storage for both sectors, the scale-up process must consider the weight, space, and safety implications of various storage options (gaseous versus liquid hydrogen) and ensure that the SOFC system is compatible with existing or planned refueling infrastructure. Implementation of SOFC systems in the maritime and aviation industries would necessitate careful system design to ensure compatibility with existing systems, as well as the development of effective fuel storage and delivery solutions. Continuous research and development are required in both sectors to address these challenges and enable the successful integration of SOFC systems. Additionally, the total lifecycle costs and environmental impact of SOFC systems in these applications must be considered [127]. This includes not only the initial costs of the SOFC systems, but also the costs of the associated infrastructure, such as fuel production and delivery systems, as well as maintenance requirements. Moreover, the environmental impact assessment should take into account not only the direct emissions from the SOFC systems, but also the emissions associated with the production of hydrogen (if it is not produced using renewable resources) [128–130], as well as the production and end-of-life disposal of the SOFC systems themselves.

The scaling-up efforts must be guided by existing and upcoming industry standards and regulations. This includes safety regulations regarding the storage and handling of hydrogen, environmental regulations regarding emissions, and technical standards concerning the performance and durability of SOFCs.

By considering these broader operational, economic, environmental, regulatory, and technological factors in the scale-up process, it is ensured that the efforts are based on a thorough comprehension of the opportunities and challenges associated with SOFC deployment in the maritime and aviation sectors.

7. Targets and Remarks

To provide a comprehensive analysis, the examination of solid oxide fuel cell-based mobility below is complemented by a brief discussion of certain Key Performance Indicators (KPIs) that have been identified as 2030 targets. These KPIs primarily focus on durability and performance prediction to offer a well-rounded assessment [131].

Based on data extracted from a report commissioned by the “Clean Hydrogen Joint Undertaking”, the state-of-the-art and projected key performance indicators (KPIs) for PEM-based propulsion are presented. However, it is important to consider these data as targets for SOFC-based propulsion technology as well. In the heavy-duty vehicles sector, the fuel cell stack durability was reported as 15,000 h in 2020, with a projection to increase to 30,000 h by 2030. Similarly, in the maritime sector, the projected fuel cell system lifetime is expected to rise from 20,000 h in 2020 to 80,000 h by 2030, with a hydrogen bunkering rate of 20. The aviation and railway sectors exhibit similar trends, with the fuel cell module durability projected to increase from 15,000 h in 2020 to 30,000 h in 2030. Regarding the durability of SOFC stacks, it can be inferred by assessing the degradation rate of performance. In 2020, the degradation rate was reported as 0.6% per 1000 h, with a projection to decrease to 0.2% per 1000 h. This improvement in stack durability is expected to result in reduced production costs, with a projected decrease from 4000 € $kW^{-1}$to less than 800 € kW^{-1}. Additionally, the electrical efficiency is anticipated to improve by approximately 10 percentage points, increasing from 47% in 2020 to 57% in 2030.

8. Conclusions

In this paper, a SOFC system was characterized and experimentally tested on a test bench. The tests were carried out at the Fuel Cell and Hydrogen Lab of the Department of Mechanical, Energy, and Management Engineering of the University of Calabria (Italy).

Through experimental activities, different findings were obtained, which constitute important parameters to characterize the fuel cell system and, in addition, in a future scale-up phase, to design SOFC applications in the transportation field. In detail, approximately 7 h were needed to heat the SOFC stack to reach 750 °C; i.e., the nominal fuel cell stack temperature. After this preliminary stage, the experimental results, carried out imposing a specific set of values on the DC load, with a rate of 1 A min^{-1}, were mainly concerned with the cell voltage, hydrogen utilization factor, and temperature. In the post-processing stage, the stack electrical and theoretical thermal powers were calculated, achieving 165 W and 80 W, respectively, and their efficiency compared to the energy provided in input by the hydrogen flow was 52% and 25% respectively.

Based on the presented analysis, it is evident that Solid Oxide Fuel Cells (SOFCs) have considerable application potential in multiple sectors of sustainable mobility, such as maritime and aviation. They have a competitive advantage over many other energy conversion technologies due to their high efficiency and fuel versatility. Therefore, the paper has discussed the technical viability of these applications, taking into account specific environmental conditions, capacity requirements, fuel storage and refueling operations, standards, regulations, and the potential for hybrid systems. In addition, the analysis encompassed the essential considerations for scaling up experimental data on SOFCs for practical applications in these industries. This included a comprehensive discussion of system durability, lifecycle costs, environmental impact, regulatory environment, and technological advancements.

SOFCs can be used for both propulsion and stationary on-board systems in the maritime industry. However, the unique conditions of the marine environment, such as corrosion from saltwater and humidity, present additional obstacles that must be overcome. Moreover, considering the marine drive cycle, SOFC systems may need to be hybridized with other energy systems in order to effectively manage dynamic loads.

The high-altitude operating environment presents a unique set of challenges to the aviation industry, including lower ambient pressure and temperature fluctuations. Similar to the maritime sector, a hybrid approach combining SOFCs with other energy systems may be required to manage the aviation drive cycle, especially to meet the high power requirements of take-off and climb.

Storage and refueling operations for SOFC systems are also essential considerations. In the maritime and aviation industries, the choice between gaseous and liquid hydrogen storage systems is largely determined by the application's specific requirements, which include weight, space, safety, and existing infrastructure. Standards and regulations, especially those pertaining to safety, play a crucial role in the application of SOFCs in these industries. These are currently underdeveloped and will require development as technology advances.

In conclusion, while the use of SOFCs in sustainable mobility offers significant potential, it also presents a number of technical and regulatory hurdles that must be overcome. To overcome these obstacles and enable the widespread adoption of SOFCs in these sectors, continued research, development, and demonstrations are required.

Further experimental investigations will concern the operation of the SOFC test bench under the supply of different gas mixtures, such as biogas and biomethane, and different operating conditions, in terms of pressure and temperature levels, in order to assess the energy performance of the system under several real-world circumstances.

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References

1. Rasul, M.G.; Hazrat, M.A.; Sattar, M.A.; Jahirul, M.I.; Shearer, M.J. The future of hydrogen: Challenges on production, storage and applications. *Energy Convers. Manag.* **2022**, *272*, 116326. [CrossRef]
2. Amin, M.; Shah, H.H.; Fareed, A.G.; Khan, W.U.; Chung, E.; Zia, A.; Rahman Farooqi, Z.U.; Lee, C. Hydrogen production through renewable and non-renewable energy processes and their impact on climate change. *Int. J. Hydrogen Energy* **2022**, *47*, 33112–33134. [CrossRef]
3. European Commission. *A European Strategy for Low-Emission Mobility*; European Commission: Brussels, Belgium, 2016.
4. Schlüter, A.; Genovese, M.; Fragiacomo, P. Preparing for More Sustainable Mobility. In *Sustainable and Smart Energy Systems for Europe's Cities and Rural Areas*; Carl Hanser Verlag GmbH & Co. KG, Ed.; Carl Hanser Verlag GmbH & Co. KG: Munich, Germany, 2022; pp. 197–216, ISBN 978-3-446-47294-5.
5. Pollet, B.G.; Kocha, S.S.; Staffell, I. Current status of automotive fuel cells for sustainable transport. *Curr. Opin. Electrochem.* **2019**, *16*, 90–95. [CrossRef]
6. Wang, Y.; Ruiz Diaz, D.F.; Chen, K.S.; Wang, Z.; Adroher, X.C. Materials, Technological Status, and Fundamentals of PEM Fuel Cells—A Review. *Mater. Today* **2020**, *32*, 178–203. [CrossRef]
7. Bessekon, Y.; Zielke, P.; Wulff, A.C.; Hagen, A. Simulation of a SOFC/Battery powered vehicle. *Int. J. Hydrogen Energy* **2019**, *44*, 1905–1918. [CrossRef]
8. Qin, X.; Cao, J.; Geng, G.; Li, Y.; Zheng, Y.; Zhang, W.; Yu, B. Solid oxide fuel cell system for automobiles. *Int. J. Green Energy* **2022**, 1–10. [CrossRef]
9. Botti, J.; Speck, C.E. *Solid Oxide Fuel Cell Power Unit for Hybrid Vehicles and Electric Vehicles—SAE Technical Paper 2005-24-094*; SAE International: Warrendale, PA, USA, 2005.
10. Ji, Z.; Qin, J.; Cheng, K.; Liu, H.; Zhang, S.; Dong, P. Design and Performance of a Compact Air-Breathing Jet Hybrid-Electric Engine Coupled with Solid Oxide Fuel Cells. *Front. Energy Res.* **2021**, *8*, 613205. [CrossRef]
11. Lindahl, P.; Moog, E.; Shaw, S.R. Simulation, Design and Validation of a UAV SOFC Propulsion System. In Proceedings of the 2009 IEEE Aerospace Conference, Big Sky, MT, USA, 7–14 March 2009; pp. 1–8.
12. Rostami, M.; Manshadi, M.D.; Farajollahi, A.H.; Marefati, M. Introducing and evaluation of a new propulsion system composed of solid oxide fuel cell and downstream cycles; usage in Unmanned Aerial Vehicles. *Int. J. Hydrogen Energy* **2022**, *47*, 13693–13709. [CrossRef]
13. Ahn, A.; Stone Welles, T.; Akih-Kumgeh, B.; Milcarek, R.J. Experimental Investigation of a Novel Combined Rapid Compression-Ignition Combustion and Solid Oxide Fuel Cell System Format Operating on Diesel. In Proceedings of the ASME 2021 Power Conference, Virtual, 20–22 July 2021; American Society of Mechanical Engineers: New York, NY, USA, 2021.
14. Sun, Y.; Anwar, M.; Hassan, N.M.S.; Spiryagin, M.; Cole, C. A review of hydrogen technologies and engineering solutions for railway vehicle design and operations. *Railw. Eng. Sci.* **2021**, *29*, 212–232. [CrossRef]
15. Piraino, F.; Fragiacomo, P. A multi-method control strategy for numerically testing a fuel cell-battery-supercapacitor tramway. *Energy Convers. Manag.* **2020**, *225*, 113481. [CrossRef]

16. Fragiacomo, P.; Piraino, F. Fuel cell hybrid powertrains for use in Southern Italian railways. *Int. J. Hydrogen Energy* **2019**, *44*, 27930–27946. [CrossRef]
17. Piraino, F.; Genovese, M.; Pagnotta, L.; Caposciutti, M.; Flaccomio Nardi Dei, L.; Fragiacomo, P. Integrated hydrogen and battery energy systems as emergency backup in electric trains. *Energy Convers. Manag. X* **2023**, *18*, 100382. [CrossRef]
18. Martinez, A.S.; Brouwer, J.; Samuelsen, G.S. Feasibility study for SOFC-GT hybrid locomotive power part II. System packaging and operating route simulation. *J. Power Sources* **2012**, *213*, 358–374. [CrossRef]
19. Ahrend, P.; Azizi, A.; Brouwer, J.; Samuelsen, G.S. A Solid Oxide Fuel Cell-Gas Turbine Hybrid System for a Freight Rail Application. In Proceedings of the ASME 2019 13th International Conference on Energy Sustainability, Bellevue, WA, USA, 15–18 July 2019; American Society of Mechanical Engineers: New York, NY, USA, 2019.
20. Schroeder, D.J.; Majumdar, P. Feasibility analysis for solid oxide fuel cells as a power source for railroad road locomotives. *Int. J. Hydrogen Energy* **2010**, *35*, 11308–11314. [CrossRef]
21. Kistner, L.; Bensmann, A.; Hanke-Rauschenbach, R. Optimal Design of a Distributed Ship Power System with Solid Oxide Fuel Cells under the Consideration of Component Malfunctions. *Appl. Energy* **2022**, *316*, 119052. [CrossRef]
22. van Veldhuizen, B.; van Biert, L.; Aravind, P.V.; Visser, K. Solid Oxide Fuel Cells for Marine Applications. *Int. J. Energy Res.* **2023**, *2023*, 5163448. [CrossRef]
23. Wang, X.; Zhu, J.; Han, M. Industrial Development Status and Prospects of the Marine Fuel Cell: A Review. *J. Mar. Sci. Eng.* **2023**, *11*, 238. [CrossRef]
24. IndustryandEnergy. EU World's First Cruise Ship Powered by Solid Oxide Fuel Cell. Available online: https://www.industryandenergy.eu/electrification/worlds-first-cruise-ship-powered-by-solid-oxide-fuel-cell/ (accessed on 12 June 2023).
25. Udomsilp, D.; Rechberger, J.; Neubauer, R.; Bischof, C.; Thaler, F.; Schafbauer, W.; Menzler, N.H.; de Haart, L.G.J.; Nenning, A.; Opitz, A.K.; et al. Metal-Supported Solid Oxide Fuel Cells with Exceptionally High Power Density for Range Extender Systems. *Cell Rep. Phys. Sci.* **2020**, *1*, 100072. [CrossRef]
26. Boldrin, P.; Brandon, N.P. Progress and outlook for solid oxide fuel cells for transportation applications. *Nat. Catal.* **2019**, *2*, 571–577. [CrossRef]
27. Tucker, M.C. Progress in metal-supported solid oxide fuel cells: A review. *J. Power Sources* **2010**, *195*, 4570–4582. [CrossRef]
28. Leah, R.T.; Bone, A.; Hammer, E.; Selcuk, A.; Rahman, M.; Clare, A.; Mukerjee, S.; Selby, M. Development Progress on the Ceres Power Steel Cell Technology Platform: Further Progress towards Commercialization. *ECS Trans.* **2017**, *78*, 87–95. [CrossRef]
29. Zhu, B.; Fan, L.; Mushtaq, N.; Raza, R.; Sajid, M.; Wu, Y.; Lin, W.; Kim, J.-S.; Lund, P.D.; Yun, S. Semiconductor Electrochemistry for Clean Energy Conversion and Storage. *Electrochem. Energy Rev.* **2021**, *4*, 757–792. [CrossRef]
30. Xing, Y.; Wu, Y.; Li, L.; Shi, Q.; Shi, J.; Yun, S.; Akbar, M.; Wang, B.; Kim, J.-S.; Zhu, B. Proton Shuttles in $CeO_2/CeO_{2-\delta}$ Core–Shell Structure. *ACS Energy Lett.* **2019**, *4*, 2601–2607. [CrossRef]
31. Wang, B.; Zhu, B.; Yun, S.; Zhang, W.; Xia, C.; Afzal, M.; Cai, Y.; Liu, Y.; Wang, Y.; Wang, H. Fast ionic conduction in semiconductor $CeO_{2-\delta}$ electrolyte fuel cells. *NPG Asia Mater.* **2019**, *11*, 51. [CrossRef]
32. Pan, Y.; Abazari, R.; Wu, Y.; Gao, J.; Zhang, Q. Advances in metal–organic frameworks and their derivatives for diverse electrocatalytic applications. *Electrochem. Commun.* **2021**, *126*, 107024. [CrossRef]
33. Yang, Q.; Lin, H.; Wang, X.; Zhang, L.Y.; Jing, M.; Yuan, W.; Li, C.M. Dynamically self-assembled adenine-mediated synthesis of pristine graphene-supported clean Pd nanoparticles with superior electrocatalytic performance toward formic acid oxidation. *J. Colloid Interface Sci.* **2022**, *613*, 515–523. [CrossRef]
34. Zhou, X.; Yang, J.; Wang, R.; Zhang, W.; Yun, S.; Wang, B. Advances in lithium-ion battery materials for ceramic fuel cells. *Energy Mater.* **2022**, *2*, 200041. [CrossRef]
35. Raza, T.; Yang, J.; Wang, R.; Xia, C.; Raza, R.; Zhu, B.; Yun, S. Recent advance in physical description and material development for single component SOFC: A mini-review. *Chem. Eng. J.* **2022**, *444*, 136533. [CrossRef]
36. Lu, Y.; Zhu, B.; Shi, J.; Yun, S. Advanced low-temperature solid oxide fuel cells based on a built-in electric field. *Energy Mater.* **2022**, *1*, 100007. [CrossRef]
37. Corigliano, O.; Pagnotta, L.; Fragiacomo, P. On the Technology of Solid Oxide Fuel Cell (SOFC) Energy Systems for Stationary Power Generation: A Review. *Sustainability* **2022**, *14*, 15276. [CrossRef]
38. Leah, R.T.; Bone, A.; Lankin, M.; Selcuk, A.; Rahman, M.; Clare, A.; Rees, L.; Phillip, S.; Mukerjee, S.; Selby, M. Ceres Power Steel Cell Technology: Rapid Progress towards a Truly Commercially Viable SOFC. *ECS Trans.* **2015**, *68*, 95–107. [CrossRef]
39. Geipel, C.; Hauptmeier, K.; Herbrig, K.; Mittmann, F.; Münch, M.; Pötschke, M.; Reichel, L.; Strohbach, T.; Seidel, T.; Surrey, A.; et al. Stack Development and Industrial Scale-Up. *ECS Trans.* **2019**, *91*, 123–132. [CrossRef]
40. Wehrle, L.; Wang, Y.; Boldrin, P.; Brandon, N.P.; Deutschmann, O.; Banerjee, A. Optimizing Solid Oxide Fuel Cell Performance to Re-evaluate Its Role in the Mobility Sector. *ACS Environ. Au* **2021**, *2*, 42–64. [CrossRef] [PubMed]
41. Kerviel, A.; Pesyridis, A.; Mohammed, A.; Chalet, D. An Evaluation of Turbocharging and Supercharging Options for High-Efficiency Fuel Cell Electric Vehicles. *Appl. Sci.* **2018**, *8*, 2474. [CrossRef]
42. Wang, Y.; Jia, C.; Lyu, Z.; Han, M.; Wu, J.; Sun, Z.; Iguchi, F.; Yashiro, K.; Kawada, T. Performance and stability analysis of SOFC containing thin and dense gadolinium-doped ceria interlayer sintered at low temperature. *J. Mater.* **2022**, *8*, 347–357. [CrossRef]

43. Chou, Y.-S.; Stevenson, J.W.; Choi, J.-P. Long-term evaluation of solid oxide fuel cell candidate materials in a 3-cell generic short stack fixture, part I: Test fixture, sealing, and electrochemical performance. *J. Power Sources* **2014**, *255*, 1–8. [CrossRef]
44. Liu, Y.; Lyu, Z.; Han, M. Optimization of Methane Reforming for High Efficiency and Stable Operation of SOFC Stacks. *ECS Trans.* **2021**, *103*, 201–209. [CrossRef]
45. Del Zotto, L.; Monforti Ferrario, A.; Hatunoglu, A.; Dell'era, A.; McPhail, S.; Bocci, E. Experimental Procedures & First Results of an Innovative Solid Oxide Fuel Cell Test Rig: Parametric Analysis and Stability Test. *Energies* **2021**, *14*, 2038. [CrossRef]
46. Fragiacomo, P.; Corigliano, O.; De Lorenzo, G.; Mirandola, F.A. Experimental Activity on a 100-W IT-SOFC Test Bench Fed by Simulated Syngas. *J. Energy Eng.* **2018**, *144*, 04018006. [CrossRef]
47. Fragiacomo, P.; De Lorenzo, G.; Corigliano, O. Performance Analysis of an Intermediate Temperature Solid Oxide Electrolyzer Test Bench under a CO_2-H_2O Feed Stream. *Energies* **2018**, *11*, 2276. [CrossRef]
48. Fragiacomo, P.; De Lorenzo, G.; Corigliano, O. Design of an SOFC/SOE station: Experimental test campaigns. *Energy Procedia* **2018**, *148*, 543–550. [CrossRef]
49. Fragiacomo, P.; Corigliano, O.; De Lorenzo, G. Design of an SOFC/SOE experimental station: Planning of simulation tests. *Energy Procedia* **2018**, *148*, 535–542. [CrossRef]
50. Corigliano, O.; Fragiacomo, P. Extensive analysis of SOFC fed by direct syngas at different anodic compositions by using two numerical approaches. *Energy Convers. Manag.* **2020**, *209*, 112664. [CrossRef]
51. Genovese, M.; Schlüter, A.; Scionti, E.; Piraino, F.; Corigliano, O.; Fragiacomo, P. Power-to-hydrogen and hydrogen-to-X energy systems for the industry of the future in Europe. *Int. J. Hydrogen Energy* **2023**, *48*, 16545–16568. [CrossRef]
52. Li, H.; Garcia, T.; Lee, M.H. Chapter 17—Solid Oxide Fuel Cells for Vehicles. In *Fuel Cells for Transportation*; Das, P.K., Jiao, K., Wang, Y., Frano, B., Li, X., Eds.; Woodhead Publishing: Sawston, UK, 2023; pp. 547–573, ISBN 978-0-323-99485-9.
53. Baldi, F.; Moret, S.; Tammi, K.; Maréchal, F. The role of solid oxide fuel cells in future ship energy systems. *Energy* **2020**, *194*, 116811. [CrossRef]
54. Henne, R.H.; Friedrich, K.A. APPLICATIONS—TRANSPORTATION | Auxiliary Power Units: Fuel Cells. In *Encyclopedia of Electrochemical Power Sources*; Garche, J., Ed.; Elsevier: Amsterdam, The Netherlands, 2009; pp. 157–173, ISBN 978-0-444-52745-5.
55. Kumar, S.S.; Aruna, S.T. Hydrocarbon Compatible SOFC Anode Catalysts and Their Syntheses: A Review. *Sustain. Chem.* **2021**, *2*, 707–763. [CrossRef]
56. 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]
57. Ma, S.; Lin, M.; Lin, T.-E.; Lan, T.; Liao, X.; Maréchal, F.; Van Herle, J.; Yang, Y.; Dong, C.; Wang, L. Fuel cell-battery hybrid systems for mobility and off-grid applications: A review. *Renew. Sustain. Energy Rev.* **2020**, *135*, 110119. [CrossRef]
58. Fragiacomo, P.; Genovese, M.; Piraino, F.; Corigliano, O.; De Lorenzo, G. Hydrogen-Fuel Cell Hybrid Powertrain: Conceptual Layouts and Current Applications. *Machines* **2022**, *10*, 1121. [CrossRef]
59. Fragiacomo, P.; Piraino, F.; Genovese, M.; Corigliano, O.; De Lorenzo, G. Strategic Overview on Fuel Cell-Based Systems for Mobility and Electrolytic Cells for Hydrogen Production. *Procedia Comput. Sci.* **2022**, *200*, 1254–1263. [CrossRef]
60. Vargas, J.E.V.; Seabra, J.E.A. Fuel-cell technologies for private vehicles in Brazil: Environmental mirage or prospective romance? A comparative life cycle assessment of PEMFC and SOFC light-duty vehicles. *Sci. Total. Environ.* **2021**, *798*, 149265. [CrossRef] [PubMed]
61. Dimitrova, Z.; Maréchal, F. Environomic design for electric vehicles with an integrated solid oxide fuel cell (SOFC) unit as a range extender. *Renew. Energy* **2017**, *112*, 124–142. [CrossRef]
62. Delphi demos SOFC tech for truck APU. *Fuel Cells Bull.* **2010**, *3*, 2010. [CrossRef]
63. Markowski, J.; Pielecha, I. The Potential of Fuel Cells as a Drive Source of Maritime Transport. In *IOP Conference Series: Earth and Environmental Science, Proceedings of the International Conference on the Sustainable Energy and Environmental Development, Krakow, Poland, 14–17 November 2017*; Institute of Physics Publishing: Bristol, UK, 2019; Volume 214, p. 214.
64. Elkafas, A.G.; Rivarolo, M.; Gadducci, E.; Magistri, L.; Massardo, A.F. Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives. *Processes* **2023**, *11*, 97. [CrossRef]
65. Di Micco, S.; Mastropasqua, L.; Cigolotti, V.; Minutillo, M.; Brouwer, J. A framework for the replacement analysis of a hydrogen-based polymer electrolyte membrane fuel cell technology on board ships: A step towards decarbonization in the maritime sector. *Energy Convers. Manag.* **2022**, *267*, 115893. [CrossRef]
66. van Biert, L.; Godjevac, M.; Visser, K.; Aravind, P.V. A review of fuel cell systems for maritime applications. *J. Power Sources* **2016**, *327*, 345–364. [CrossRef]
67. Sapra, H.; Stam, J.; Reurings, J.; van Biert, L.; van Sluijs, W.; de Vos, P.; Visser, K.; Vellayani, A.P.; Hopman, H. Integration of solid oxide fuel cell and internal combustion engine for maritime applications. *Appl. Energy* **2021**, *281*, 115854. [CrossRef]
68. International Energy Agency IEA. *International Shipping*; International Energy Agency: Paris, France, 2022.
69. Micoli, L.; Coppola, T.; Turco, M. A Case Study of a Solid Oxide Fuel Cell Plant on Board a Cruise Ship. *J. Mar. Sci. Appl.* **2021**, *20*, 524–533. [CrossRef]
70. Minh, N.Q. 8—Cell and Stack Design, Fabrication and Performance. In *High-Temperature Solid Oxide Fuel Cells for the 21st Century*, 2nd ed.; Kendall, K., Kendall, M., Eds.; Academic Press: Boston, MA, USA, 2016; pp. 255–282, ISBN 978-0-12-410453-2.

71. Minh, N.Q. Reversible Solid Oxide Cell Technology. In *Encyclopedia of Energy Storage*; Cabeza, L.F., Ed.; Elsevier: Oxford, UK, 2022; pp. 338–343, ISBN 978-0-12-819730-1.
72. Aicher, T.; Lenz, B.; Gschnell, F.; Groos, U.; Federici, F.; Caprile, L.; Parodi, L. Fuel processors for fuel cell APU applications. *J. Power Sources* **2006**, *154*, 503–508. [CrossRef]
73. Fallah Vostakola, M.; Amini Horri, B. Progress in Material Development for Low-Temperature Solid Oxide Fuel Cells: A Review. *Energies* **2021**, *14*, 1280. [CrossRef]
74. Eichhorn Colombo, K.W.; Kharton, V.V. Start-Up of a Solid Oxide Fuel Cell System with a View to Materials Science-Related Aspects, Control and Thermo-Mechanical Stresses. *Crystals* **2021**, *11*, 732. [CrossRef]
75. Huang, Y.L.; Pellegrinelli, C.; Wachsman, E.D. Fundamental Impact of Humidity on SOFC Cathode ORR. *J. Electrochem. Soc.* **2016**, *163*, F171–F182. [CrossRef]
76. IMO. IMO—International Maritime Organization. Available online: https://www.imo.org/ (accessed on 9 June 2023).
77. Fu, Z.; Lu, L.; Zhang, C.; Xu, Q.; Zhang, X.; Gao, Z.; Li, J. Fuel cell and hydrogen in maritime application: A review on aspects of technology, cost and regulations. *Sustain. Energy Technol. Assess.* **2023**, *57*, 103181. [CrossRef]
78. Pomaska, L.; Acciaro, M. Bridging the Maritime-Hydrogen Cost-Gap: Real options analysis of policy alternatives. *Transp. Res. Part D Transp. Environ.* **2022**, *107*, 103283. [CrossRef]
79. Xing, H.; Stuart, C.; Spence, S.; Chen, H. Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *J. Clean. Prod.* **2021**, *297*, 126651. [CrossRef]
80. Zanobetti, F.; Pio, G.; Jafarzadeh, S.; Ortiz, M.M.; Cozzani, V. Inherent safety of clean fuels for maritime transport. *Process. Saf. Environ. Prot.* **2023**, *174*, 1044–1055. [CrossRef]
81. Molkov, V. 4.04—Hydrogen Safety Engineering and Standards. In *Comprehensive Renewable Energy*, 2nd ed.; Letcher, T.M., Ed.; Elsevier: Oxford, UK, 2022; pp. 86–118, ISBN 978-0-12-819734-9.
82. Dagdougui, H.; Sacile, R.; Bersani, C.; Ouammi, A. Hydrogen Logistics: Safety and Risks Issues. In *Hydrogen Infrastructure for Energy Applications*; Academic Press: Cambridge, MA, USA, 2018. [CrossRef]
83. Hübert, T.; Boon-Brett, L.; Palmisano, V.; Bader, M.A. Developments in Gas Sensor Technology for Hydrogen Safety. *Proc. Int. J. Hydrog. Energy* **2014**, *39*, 20474–20483. [CrossRef]
84. Buttner, W.J.; Post, M.B.; Burgess, R.; Rivkin, C. An overview of hydrogen safety sensors and requirements. *Int. J. Hydrogen Energy* **2011**, *36*, 2462–2470. [CrossRef]
85. Duong, P.A.; Ryu, B.; Kim, C.; Lee, J.; Kang, H. Energy and Exergy Analysis of an Ammonia Fuel Cell Integrated System for Marine Vessels. *Energies* **2022**, *15*, 3331. [CrossRef]
86. Barelli, L.; Bidini, G.; Cinti, G. Operation of a Solid Oxide Fuel Cell Based Power System with Ammonia as a Fuel: Experimental Test and System Design. *Energies* **2020**, *13*, 6173. [CrossRef]
87. McKinlay, C.J.; Turnock, S.R.; Hudson, D.A. Route to zero emission shipping: Hydrogen, ammonia or methanol? *Int. J. Hydrogen Energy* **2021**, *46*, 28282–28297. [CrossRef]
88. Genovese, M.; Cigolotti, V.; Jannelli, E.; Fragiacomo, P. Hydrogen Refueling Process: Theory, Modeling, and In-Force Applications. *Energies* **2023**, *16*, 2890. [CrossRef]
89. Wang, X.; Fu, J.; Liu, Z.; Liu, J. Review of researches on important components of hydrogen supply systems and rapid hydrogen refueling processes. *Int. J. Hydrogen Energy* **2023**, *48*, 1904–1929. [CrossRef]
90. Alkhaledi, A.N.; Sampath, S.; Pilidis, P. Propulsion of a hydrogen-fuelled LH2 tanker ship. *Int. J. Hydrogen Energy* **2022**, *47*, 17407–17422. [CrossRef]
91. Baldi, F.; Ahlgren, F.; Nguyen, T.-V.; Thern, M.; Andersson, K. Energy and Exergy Analysis of a Cruise Ship. *Energies* **2018**, *11*, 2508. [CrossRef]
92. Soriani, S.; Bertazzon, S.; DI Cesare, F.; Rech, G. Cruising in the Mediterranean: Structural aspects and evolutionary trends. *Marit. Policy Manag.* **2009**, *36*, 235–251. [CrossRef]
93. Borén, C.; Castells-Sanabra, M.; Grifoll, M. Ship emissions reduction using weather ship routing optimisation. *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.* **2022**, *236*, 856–867. [CrossRef]
94. Ruf, Y.; Kaufmann, M.; Lange, S.; Pfister, J.; Heieck, F.; Endres Brussels, A. Fuel Cells and Hydrogen Applications for Regions and Cities. *Eur. Union Fuel Cells Hydrogen* **2017**, *1*, 108–123.
95. Ramasubramanian, B.; Rao, R.P.; Chellappan, V.; Ramakrishna, S. Towards Sustainable Fuel Cells and Batteries with an AI Perspective. *Sustainability* **2022**, *14*, 16001. [CrossRef]
96. Benet, Á.; Villalba-Herreros, A.; D'amore-Domenech, R.; Leo, T.J. Knowledge gaps in fuel cell-based maritime hybrid power plants and alternative fuels. *J. Power Sources* **2022**, *548*, 232066. [CrossRef]
97. Chehrmonavari, H.; Kakaee, A.; Hosseini, S.E.; Desideri, U.; Tsatsaronis, G.; Floerchinger, G.; Braun, R.; Paykani, A. Hybridizing solid oxide fuel cells with internal combustion engines for power and propulsion systems: A review. *Renew. Sustain. Energy Rev.* **2023**, *171*, 112982. [CrossRef]
98. Haseltalab, A.; van Biert, L.; Sapra, H.; Mestemaker, B.; Negenborn, R.R. Component sizing and energy management for SOFC-based ship power systems. *Energy Convers. Manag.* **2021**, *245*, 114625. [CrossRef]

99. Wang, Z.; Zhao, F.; Ma, Y.; Xia, R.; Han, F. Performance Analysis and Design of Direct Ammonia Fuel Tubular Solid Oxide Fuel Cell for Shipborne Unmanned Aerial Vehicles. *Aerospace* **2023**, *10*, 397. [CrossRef]
100. Hosseini, S.E. 4.12—Hydrogen and Fuel Cells in Transport Road, Rail, Air, and Sea. In *Comprehensive Renewable Energy*, 2nd ed.; Letcher, T.M., Ed.; Elsevier: Oxford, UK, 2022; pp. 317–342, ISBN 978-0-12-819734-9.
101. Afonso, F.; Sohst, M.; Diogo, C.M.; Rodrigues, S.S.; Ferreira, A.; Ribeiro, I.; Marques, R.; Rego, F.F.; Sohouli, A.; Portugal-Pereira, J.; et al. Strategies towards a more sustainable aviation: A systematic review. *Prog. Aerosp. Sci.* **2023**, *137*, 100878. [CrossRef]
102. Müller-Casseres, E.; Szklo, A.; Fonte, C.; Carvalho, F.; Portugal-Pereira, J.; Baptista, L.B.; Maia, P.; Rochedo, P.R.; Draeger, R.; Schaeffer, R. Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil. *iScience* **2022**, *25*, 105248. [CrossRef] [PubMed]
103. Airbus announces plans to decarbonise air travel. *Fuel Cells Bull.* **2021**, *2021*, 10. [CrossRef]
104. Airbus studies fuel cell pods for future aircraft. *Fuel Cells Bull.* **2021**, *2021*, 6. [CrossRef]
105. Fernandes; Andrade, S.T.D.P.; Bistritzki, V.N.; Fonseca, R.M.; Zacarias, L.G.; Gonçalves, H.N.C.; 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]
106. Baroutaji, A.; Wilberforce, T.; Ramadan, M.; Olabi, A.G. Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. *Renew. Sustain. Energy Rev.* **2019**, *106*, 31–40. [CrossRef]
107. Coutinho, M.; Bento, D.; Souza, A.; Cruz, R.; Afonso, F.; Lau, F.; Suleman, A.; Barbosa, F.R.; Gandolfi, R.; Affonso, W.; et al. A review on the recent developments in thermal management systems for hybrid-electric aircraft. *Appl. Therm. Eng.* **2023**, *227*, 120427. [CrossRef]
108. Mendonça, C.; Ferreira, A.; Santos, D.M.F. Towards the Commercialization of Solid Oxide Fuel Cells: Recent Advances in Materials and Integration Strategies. *Fuels* **2021**, *2*, 393–419. [CrossRef]
109. FAA Federal Aviation Administration. Available online: https://www.faa.gov/ (accessed on 9 June 2023).
110. EASA European Union Aviation Safety Agency. Available online: https://www.easa.europa.eu/en/regulations (accessed on 9 June 2023).
111. Prewitz, M.; Schwärzer, J.; Bardenhagen, A. Potential analysis of hydrogen storage systems in aircraft design. *Int. J. Hydrogen Energy* **2023**, *48*, 25538–25548. [CrossRef]
112. Genovese, M.; Fragiacomo, P. Hydrogen refueling station: Overview of the technological status and research enhancement. *J. Energy Storage* **2023**, *61*, 106758. [CrossRef]
113. Genovese, M.; Cigolotti, V.; Jannelli, E.; Fragiacomo, P. Current standards and configurations for the permitting and operation of hydrogen refueling stations. *Int. J. Hydrogen Energy* **2023**, *48*, 19357–19371. [CrossRef]
114. Collins, J.M.; McLarty, D. All-electric commercial aviation with solid oxide fuel cell-gas turbine-battery hybrids. *Appl. Energy* **2020**, *265*, 114787. [CrossRef]
115. Gray, N.; McDonagh, S.; O'Shea, R.; Smyth, B.; Murphy, J.D. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Adv. Appl. Energy* **2021**, *1*, 100008. [CrossRef]
116. Liu, H.; Qin, J.; Ji, Z.; Guo, F.; Dong, P. Study on the performance comparison of three configurations of aviation fuel cell gas turbine hybrid power generation system. *J. Power Sources* **2021**, *501*, 230007. [CrossRef]
117. Bahari, M.; Rostami, M.; Entezari, A.; Ghahremani, S.; Etminan, M. A comparative analysis and optimization of two supersonic hybrid SOFC and turbine-less jet engine propulsion system for UAV. *Fuel* **2022**, *319*, 123796. [CrossRef]
118. Liu, H.; Qin, J.; Xiu, X.; Ha, C.; Dong, P. Comparative study of fuel types on solid oxide fuel cell—Gas turbine hybrid system for electric propulsion aircraft. *Fuel* **2023**, *347*, 128426. [CrossRef]
119. Liu, H.; Qin, J.; Li, C.; Guo, F.; Dong, P. Influence of fuel reforming with low water to carbon ratio on thermodynamic performance of aviation solid oxide fuel cell—Gas turbine hybrid system. *J. Power Sources* **2022**, *546*, 231978. [CrossRef]
120. Li, C.; Cheng, K.; Ma, S.; Liu, H.; Ji, Z.; Qin, J. Performance analysis of solid oxide fuel cell/piston engine hybrid system for aviation. *Appl. Therm. Eng.* **2022**, *214*, 118797. [CrossRef]
121. Cui, L.; Huo, H.; Xie, G.; Xu, J.; Kuang, X.; Dong, Z. Long-Term Degradation Trend Prediction and Remaining Useful Life Estimation for Solid Oxide Fuel Cells. *Sustainability* **2022**, *14*, 9069. [CrossRef]
122. Staffolani, A.; Baldinelli, A.; Barelli, L.; Bidini, G.; Nobili, F. Early-Stage Detection of Solid Oxide Cells Anode Degradation by *Operando* Impedance Analysis. *Processes* **2021**, *9*, 848. [CrossRef]
123. Peng, J.; Zhao, D.; Xu, Y.; Wu, X.; Li, X. Comprehensive Analysis of Solid Oxide Fuel Cell Performance Degradation Mechanism, Prediction, and Optimization Studies. *Energies* **2023**, *16*, 788. [CrossRef]
124. Ryu, B.R.; Duong, P.A.; Kang, H. Comparative analysis of the thermodynamic performances of solid oxide fuel cell–gas turbine integrated systems for marine vessels using ammonia and hydrogen as fuels. *Int. J. Nav. Arch. Ocean Eng.* **2023**, *15*, 100524. [CrossRef]
125. Rivarolo, M.; Rattazzi, D.; Magistri, L. Best operative strategy for energy management of a cruise ship employing different distributed generation technologies. *Int. J. Hydrogen Energy* **2018**, *43*, 23500–23510. [CrossRef]
126. Gianni, M.; Pietra, A.; Coraddu, A.; Taccani, R. Impact of SOFC Power Generation Plant on Carbon Intensity Index (CII) Calculation for Cruise Ships. *J. Mar. Sci. Eng.* **2022**, *10*, 1478. [CrossRef]

127. Salim, K.M.A.; Maelah, R.; Hishamuddin, H.; Amir, A.M.; Ab Rahman, M.N. Two Decades of Life Cycle Sustainability Assessment of Solid Oxide Fuel Cells (SOFCs): A Review. *Sustainability* **2022**, *14*, 12380. [CrossRef]
128. Perčić, M.; Vladimir, N.; Jovanović, I.; Koričan, M. Application of fuel cells with zero-carbon fuels in short-sea shipping. *Appl. Energy* **2022**, *309*, 118463. [CrossRef]
129. Wang, Y.; Maidment, H.; Boccolini, V.; Wright, L. Life cycle assessment of alternative marine fuels for super yacht. *Reg. Stud. Mar. Sci.* **2022**, *55*, 102525. [CrossRef]
130. Wang, Y.; Cao, Q.; Liu, L.; Wu, Y.; Liu, H.; Gu, Z.; Zhu, C. A review of low and zero carbon fuel technologies: Achieving ship carbon reduction targets. *Sustain. Energy Technol. Assess.* **2022**, *54*, 102762. [CrossRef]
131. *Clean Hydrogen Joint Undertaking Strategic Research and Innovation Agenda 2021–2027*; Clean Hydrogen Partnership: Brussels, Belgium, 2022. Available online: https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en (accessed on 12 June 2023).