sustainability

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Comparative Analysis of Direct Operating Costs: Conventional vs. Hydrogen Fuel Cell 19-Seat Aircraft

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Abstract: In this paper, a comparative analysis of direct operating costs between a 19-seat conventional and hydrogen-powered fuel cell aircraft is performed by developing a model to estimate direct operating costs and considering the evolution of costs over time from 2030 to 2050. However, due to the technology being in its early stages of development and implementation, there are still considerable uncertainties surrounding the direct operating costs of hydrogen aircraft. To address this, the study considers high and low kerosene growth rates and optimistic and pessimistic development scenarios for hydrogen fuel cell aircraft, while also considering the evolution of costs over time. The comparative analysis uses real flight and aircraft data for the airliner Trade Air. The results show that the use of 19-seat hydrogen fuel cell aircraft for air transportation is a viable option when compared to conventional aircraft. Additionally, the study suggests potential policies and other measures that could accelerate the adoption of hydrogen fuel cell technology by considering their direct operating costs.

Keywords: fuel cell aircraft; direct operating cost of aircraft; 19-seat aircraft

Citation: Maršenka, M.; Prapotnik Brdnik, A. Comparative Analysis of Direct Operating Costs: Conventional vs. Hydrogen Fuel Cell 19-Seat Aircraft. *Sustainability* **2023**, *15*, 11271. https://doi.org/10.3390/su151411271

Academic Editors: T. Hikmet Karakoç, Selcuk Ekici, Ozgur Balli and Alper Dalkiran

Received: 1 June 2023
Revised: 17 July 2023
Accepted: 18 July 2023
Published: 19 July 2023

1. Introduction

In recent years, there has been significant growth in air traffic. In February 2023, the total revenue passenger kilometers of air traffic increased by 55.5% compared to the same period in 2022. Additionally, domestic air travel has demonstrated an impressive recovery, with a 97.2% resurgence in February 2023 compared to the same month in 2019 [1]. Despite occasional interruptions, the demand for air travel is projected to continue growing steadily, with an estimated growth rate of about 4% in 2024 compared to the demand in 2019 [2]. This surge in air travel demand could pose a challenge to long-term efforts to reduce environmental impact and could especially undermine the achievement of key objectives outlined in the European Green Deal, the goal of which is the reduction of greenhouse gas emissions by at least 55% by 2030 and achieving climate neutrality by 2050 [3].

To mitigate the adverse environmental effects of aviation, significant technological advancements have been made in the direction of reducing fuel consumption and improving aircraft performance. These efforts include the development of newer engines, the use of lightweight composite materials for the fuselage design, and the implementation of more efficient flight procedures, among others [4–9]. All of these technological developments are improving existing technology in terms of fuel consumption, efficiency, etc. On the other hand, to minimize negative emissions from aviation, particularly CO_2 and NO_X, new revolutionary propulsion technologies have been developed. Numerous projects and studies have been proposed and conducted to find suitable alternatives to fossil fuels such as batteries, hydrogen, and synthetic fuels and/or ICE propulsion technology such as electric motors, fuel cells, and hybrid systems. The suitability of these solutions may vary from one application to another. For example, battery-powered aircraft are a suitable solution for small general aviation aircraft due to the low energy density of batteries but are unsuitable for large long-range aircraft.

In addition to battery-powered aircraft, a very interesting technology that leaves no environmental footprint is the hydrogen fuel cell aircraft. In fuel cells, hydrogen is consumed and electricity is generated. The electricity generated is then used by an electric motor to drive a propeller. Since the fuel cell produces only water vapor as a byproduct, the fuel cell aircraft can be considered environmentally friendly with zero CO_2 emissions. However, this is only the case if the hydrogen is produced in an environmentally friendly manner from renewable energy sources (green hydrogen).

While in the medium term, it will be sufficient to minimize emissions solely by improving existing aviation technologies, in the long-term, revolutionary technologies will be needed to achieve the political goals under the European Green Deal [10,11]. Therefore, the commercialization of emerging technologies, such as fuel cell aircraft, is key to reducing aviation's impact on the climate. However, their success depends on achieving operating costs that are competitive with those of conventional aircraft. As the technology matures, the challenge will be to scale up production and deployment so that airlines can adopt it on a meaningful level. Unfortunately, investing in a new propulsion system like hydrogen fuel cells is inherently risky, and manufacturers will be hesitant to do so if airlines are not interested in buying their aircraft. On the other hand, airlines will only consider purchasing these aircraft if they meet certain criteria, such as suitable seating capacity, performance characteristics (e.g., range, speed, rate of climb), and operating costs. Currently, the financial viability of hydrogen-powered aircraft is largely unknown, which leaves both airlines and policymakers without sufficient information to make informed investment decisions. To bring these planes to market and reduce the environmental impact of air travel, it is critical to better understand the capital and operating costs associated with this new technology and develop financial initiatives that can support its development and adoption.

1.1. Technological Development of Hydrogen Aircraft

However, the direct operating costs of hydrogen aircraft are still subject to significant uncertainties, as the technology is still in the early stages of development and implementation. Nonetheless, technological aspects of fuel cell aircraft have been studied in tested various ways. The performance characteristics and MTOM of fuel cell aircraft have been studied by [12–14]. The study by Trainelli et al. [13] showed that using the existing aircraft design of 4- and 11-seat aircraft and converting it to a fuel cell aircraft would result in a significant degradation of mission performance. A study by Vonhoff [14] showed that 19-seat fuel cell aircraft could be built with a similar MTOM to conventional aircraft, while an 11-seat fuel cell aircraft would have a larger MTOM than an 11-seat conventional aircraft. The study by Marksel and Prapotnik Brdnik [12] showed that the MTOM of a 19-seat fuel cell aircraft is highly dependent on the power-to-weight ratio of the fuel cell and can be either 25% higher than the MTOM of a comparable conventional 19-seat aircraft or even lower than the MTOM of comparable conventional 19-seat aircraft if the power-to-weight ratio of fuel cell will improve as predicted in the future. The study also showed that the fuel cell aircraft favors lower power loading.

The cryogenic storage system was studied by [15–18]. The studies by Verstreate et al. [15] and Winnefeld et al. [16] both propose a single hydrogen tank of cylindrical shape and circular cross-section integrated into the fuselage, while the study by Silberhorn [17] proposes pod tanks.

The hydrogen fuel cell has been studied, based on multi-criteria decision-making methods (MCDM) that were based on power-related criteria such as specific power and power capacity. PEM fuel cells were determined to be the most suitable for integration into hybrid aircraft [19]. Other researchers evaluated different fuel cell types for electrified aviation, and identified solid oxide, high-temperature, and low-temperature polymer electrolyte membrane fuel cells as promising options based on aviation-specific requirements, and highlighted design challenges such as cold start, cooling, and pressurized air supply [20].

In addition to theoretical studies, fuel cell technology has also been practically applied to small aircraft. The first prototype of a two-seater fuel cell aircraft was the DLR-H2, which was tested in 2009 [21]. This was followed by the development of several prototypes, including the four-seater HY4 prototype in 2016 [22], a four-seater prototype by Zero Avia in 2020 [23], and the Phoenix small aircraft prototype, which utilizes fuel cells with liquid hydrogen, in 2022 [24]. The successful test flight of a 19-seater aircraft powered by hydrogen fuel cells by ZeroAvia in 2030 represents the most significant accomplishment in the deployment of fuel cell technology to date, in terms of aircraft size [25]. In the future, various companies such as ZeroAvia, H2FLY, NASA, Alaka'i Technologies, HES Energy Systems, and Airbus have announced fuel cell-powered technologies. Although there has been substantial progress in the field of hydrogen-powered aviation, the development of such an aircraft is not expected before 2030-2035 due to factors such as technological readiness, mass production of aircraft, cost of liquid hydrogen, kerosene, and electricity, infrastructure requirements, and others [26].

1.2. Economical Studies of Hydrogen Aircraft

Research on the operating and capital costs of hydrogen aircraft, especially fuel cell aircraft, has been relatively scarce compared to electric and hybrid electric aircraft. Several studies [27–30] investigated the operating and capital costs of electric and hybrid electric aircraft. Nevertheless, equivalent studies are still limited for hydrogen aircraft, particularly fuel cell aircraft. The most recent research on hydrogen-powered aviation has explored the potential use of hydrogen-powered aircraft, considering factors such as technical feasibility, economics, and market readiness. Several studies attempted to estimate the total cost of hydrogen-powered aircraft compared to conventional aircraft, including a 19-seat turboprop configuration with fuel cells [26]. Some preliminary studies investigated the total cost of ownership of hydrogen fuel cell aircraft, specifically focusing on smaller 4-seater regional aircraft. These studies found that hydrogen fuel cell aircraft have lower capital and operating costs compared to conventional aircraft. In addition, they showed that the propulsion system consisting of hydrogen fuel cells and an electric motor can have comparable performance and cost characteristics to the piston engine-based propulsion system in regional aircraft [31]. However, these studies are conducted on a specific aircraft type and often just quote the results without presenting a detailed model.

None of these studies developed detailed cost models for aircraft that could analyze different fuel price scenarios or the development of fuel cell aircraft. While they highlighted the economic advantages of using hydrogen cells compared to other technologies, a more comprehensive analysis is needed to fully understand the potential cost benefits.

The purpose of this research is to conduct a comparative analysis of direct operating costs for both conventional 19-seat aircraft and hydrogen fuel cell aircraft using real flight data, while also projecting changes in the direct operating cost over time. We specifically chose this aircraft size because it falls under less stringent regulations, such as FAR–23/EASA CS-23, which enables a faster and simpler certification process compared to larger aircraft. Another advantage is that the technology has already undergone flight testing on 19-seat aircraft, providing us with more reliable data for our study. This research aims to provide insight into the cost categories and development factors that are crucial in the implementation of fuel cell aircraft for commercial air services, as well as the policy measures for adopting fuel cell aircraft. Section 2 establishes the baseline by examining the airliners and their fleets in Europe. This information is used to prepare the direct cost model, which is described in Section 3. The methodology for calculating the direct operating costs of both conventional and fuel cell aircraft is detailed in this section. The results of the analysis are presented and discussed in Section 4. Finally, Section 5 summarizes the conclusions of the study.

2. Carriers Operating 19-Seat Aircraft in Europe

There are three companies that still manufacture 19-seat aircraft: Aircraft Industries (formerly Let Kunovice) of the Czech Republic, Dornier of Germany, and de Havilland Canada. Basic data on their latest models are summarised in Table 1. In addition, Table 1 also includes data on three aircraft types that are no longer in production but are still in service: Beachcraft, British Aerospace Jetstream, and Fairchild Swearing Metroliner. From the data, it appears that the aircraft have similar characteristics, with MTOM varying from 5600 kg to 7764 kg, power loading ranging from 0.18 kW/kg to 0.25, kW/kg, wing loading varying from 150 kg/m^2 to 280 kg/m^2, and ferry range ranging from 1000 km to nearly 3000 km.

Table 1. List of 19-seat turboprop aircraft and their characteristics: year of the production of the last model, maximal take-off mass (MTOM), Ferry range (R), power loading (P/MTOM), and wing loading (MTOM/S_w). † No longer in production, but still in service.

Name	Code	Year	MTOM [kg]	R [km]	P/MTOM [kW/kg]	MTOM/S_w [kg/m^2]
Aircraft Industries L410 NG [32]	L410	2010	7000	2750	0.181	201
DHC-6 Twin Otter [33]	DHC	2010	5670	1480	0.197	145
Dornier 228 NG [34]	D28	2009	6575	2363	0.176	205
Beechcraft 1900D † [35]	BET	1984	7764	2306	0.246	270
British Aerospace Jetstream † [36]	BEJ	1980	6600	1260	0.202	276
Fairchild Swearingen Metroliner † [37]	FSM	1969	6577	1100	0.228	227

The list of European carriers operating 19-seat aircraft identified in the 2017 OAG database [38] is included in Table 2. The list includes only those companies that operated scheduled flights in 2017 and still operate at least one 19-seat aircraft. Companies that operated scheduled flights with 19-seat aircraft in 2017 but no longer own 19-seat aircraft, as well as companies that began operating 19-seat aircraft after 2017 or do not operate scheduled flights, are not included in Table 2. In addition, Table 2 includes data on scheduled flights only. Data on other types of services (e.g., charter flights, taxis, business aviation) are not included. The majority of flights operated with 19-seat aircraft are national. Most companies are based in the country in which they operate, with the exception of the Lithuanian company Transaviabaltika, which operates in Estonia, and two Czech companies, Silverair, which operates in Italy, and Van Air Europe which operates in the UK. Most companies operate in Northern Europe (United Kingdom, Iceland, Scandinavia) and provide connections between places that are difficult to reach by other means (e.g., islands, bad weather conditions). However, there are two major airlines operating in Western Europe (Portugal and France) and one Czech carrier operating in Italy.

Table 2. List of European carriers operating with 19-seat aircraft that provided scheduled flights in 2017 [38] and their characteristics: country in which they operated in 2017, number of all aircraft in the fleet (N), number of 19-seat aircraft in the fleet (N_{19}), type of 19-seat aircraft they operate by code (see Table 1), minimal (average) and maximal flight distance (R), annual flight time per 19-seat aircraft (FT), the annual number of flights performed by all 19-seat aircraft (N_F). † Only two aircraft were taken into account in the calculation, as a third aircraft was purchased later. ‡ Includes flights of Hex'Air which merged with Twin Jet at the beginning of 2017. * Does not include stored aircraft.

Name	Country	N	N_{19}	Aircraft by Code	R [km]	FT [h]	N_F
Aurigny [39]	UK, France	6	2	D28	40 (87) 151	1365	5774
Eagle Air [40]	Iceland	6	3	BEJ	113 (222) 325	915	3876
Isles of Scilly Skybus [41]	UK	7	4	DHC	48 (105) 224	735	5482
Loganair [42]	UK	42	3	DHC	92 (165) 224	398	1226

Table 2. *Cont.*

Name	**Country**	N	N_{19}	**Aircraft by Code**	R **[km]**	FT **[h]**	N_F
Norlandair [43]	Iceland	5	3	DHC	60 (109) 150	315 †	1132
Sevenair Air Services [44]	Portugal	14 *	3 *	D28, BEJ	60 (120) 610	870 *	6958
Silver Air [45]	Italy	2	2	L410	101 (180) 375	216	447
Trade Air [46]	Croatia	7	1	L410	193 (247) 386	1309	1664
Transaviabaltika [47]	Estonia	2	2	BEJ	122 (154) 187	720	2461
Twin Jet ‡ [48]	French, Germany	13	13	BEH	248 (484) 772	818	7616
Van Air Europe [49]	UK	5	5	L410	100 (166) 293	201	1182

Airline service ranges from 40 km to 800 km. The annual flight hours per aircraft listed in Table 2 range from 200 to 1400 and are calculated by dividing the number of flights in 2017 obtained from the OAG database [38] by the number of 19-seat aircraft the companies own today. However, the actual annual flight hours per aircraft are higher than shown in Table 2 for the following reasons: The OAG base includes only scheduled flights, and the airlines listed in Table 2 provide other services (e.g., charter flights, business flights); the companies may have acquired additional 19-seat aircraft after 2017; or the fleet includes aircraft that are on loan to another company and therefore double counted (example: Van Air Europe leases aircraft to Trade Air). For comparison, the average utilization of turboprop and regional aircraft in 2019 was 6 h per day [50], which is equivalent to 1560 annual flight hours if the aircraft operates Monday through Friday.

The case study on direct operating costs, including airport charges, is conducted on the Croatian airline Trade Air [46]. Trade Air is a registered airline whose main activities are passenger charter flights and cargo operations. Its fleet consists of two Airbus aircraft (150 and 180 passengers), a Fokker 100, and an Aircraft Industries L410 leased from Van Air Europe. The company operates scheduled domestic flights according to the following schedule [38,46]:

- on Mondays and Fridays the carrier operates on the relation. Osijek–Zagreb–Osjek–Pula–Split–Pula–Osjek–Zagreb–Osjek.
- On Tuesday and Thursday the carrier operates on the relation Osijek–Rijeka–Split–Dubrovik–Split–Rijeka–Osjek.
- On Wednesday the aircraft performs two return flights Osjek–Zagreb–Osjek, one in the morning and one in the evening.

The route data are given in Table 3. The airline flies all year round. From the flight schedule it can also be deduced that the time between flights is 30 min.

Table 3. Trade air sheduled flight routes: distance (R_i), flight time in both directions (FT_{i1}, FT_{i2}), number of round-trip flights per year $N_{F,i}$.

Route	R_i **[km]**	FT_{i1} **[min]**	$FT2_{i2}$ **[min]**	$N_{F,i}$
Zagreb–Osjek	214	45	40	312
Osjek–Pula	386	75	75	104
Osjek–Rijeka	332	65	50	104
Pula–Split	240	50	50	104
Rijeka–Split	230	40	50	104
Split–Dubrovnik	193	45	40	104

3. Direct Operating Cost

Airline operating costs can be divided into direct operating costs (DOC), which include all aircraft-related costs, and indirect operating costs (IOC), which include passenger-related costs (e.g., ticketing costs). The division of costs between DOC and IOC is not always clear, so different methods use different approaches [51]. Since aircraft replacement only affects DOC, this paper only examines DOC. There are several methods for calculating DOC, including the method developed by Lufthansa in 1982 (DLH 1982), the method developed by the Association of European Airliners in 1989 (AEA 1989), the method developed by Airbus Industries in 1989 (AI 1989), and the method developed by Fokker in 1993 (Fokker 1993) [51]. Although all of these methods are more appropriate for calculating DOC of larger commercial aircraft and cannot be fully applied to 19-seat aircraft, they provide a good basis for DOC estimation of 19-seat aircraft. The methods are used to decide which cost elements to include in the calculation of DOC, but instead of using semiempirical formulas and values suggested by the above methods, real data for 19-seat airplanes are obtained. Furthermore, the DOC calculation method is then adopted for 19-seat fuel cell aircraft. Following the above methods, annual DOC ($C_{DOC,a}$) include annual depreciation (C_{DEP}), annual interest cost (C_{INT}), annnual insurance cost (C_{INS}), annual fuel cost (C_{FUEL}), annual maintenance cost (C_M), annual crew cost (C_C), and annual fees and charges cost (C_{FEE}) [51]:

$$C_{DOC,a} = C_{DEP} + C_{INS} + C_{INT} + C_{FUEL} + C_M + C_C + C_{FEE}\,. \tag{1}$$

3.1. Depreciation, Insurance and Interest Cost

The cost of depreciation (C_{DEP}), insurance (C_{INS}) and interest (C_{INT}) depends on the purchase price of the aircraft, is calculated annually, and does not depend on the flight schedule:

$$C_{DEP} + C_{INS} + C_{INT} = \left(\frac{0.9}{N_{LY}} + k_{INS} + k_{INT}\right) P_A \tag{2}$$

where P_A is the purchase price of aircraft, N_{LY} is the useful life of the aircraft, and k_{INS} and k_{INT} are the annual insurance and interest rates. The purchase prices of the conventional 19-seat aircraft still in production are shown in Table 4, while the purchase prices of the 19-seat fuel cell aircraft are predicted using the methodology described in Section 3.2.

Table 4. The purchase price of 19-seat aircraft. The prices are obtained from the production companies.

Aircraft type	L410	DHC	D228
Price [EUR]	6,455,884	5,762,358	5,793,742

The Equation (2) takes into account that aircraft can still be sold at a residual price of 10% of the value of new aircraft after the end of their service life, as suggested by the AEA, Fokker, and AI methods. Aircraft retirement rates depend on aircraft type and date of manufacture. The expected life of aircraft was estimated to be 14 years under the DLH and AEA models and 15 years under the AI and Fokker models [51]. However, with technological advances, aircraft life is extended. According to the ICAO model, 70% of regional turboprop aircraft will remain in service for more than 20 years, while 50% of regional turboprop aircraft will retire after 29 years [52]. In one study [53], the retirement rate of turboprop aircraft is given as 20 years. Therefore, in this study, we assume an operational life of 20 years.

The annual interest rate is estimated to be between 5% and 6% according to the DLH, AEA, and Fokker models, which is comparable to recent data on interest rates for turboprop aircraft purchases, which are between 4% and 5% [54]. In this study, we take $k_{INT} = 0.05$.

Annual insurance costs are estimated at 0.5% of the aircraft purchase price for the AEA and AI models, 0.56% of the aircraft purchase price for the DLH model, and 0.4% of the aircraft purchase price for the Fokker model. Nevertheless, annual insurance rates began to increase significantly after 2018 [55]. In this study, annual insurance costs were estimated using direct operating cost data for the L410 NG aircraft, obtained directly from the manufacturer, which included both insurance and management fees [56]. According to [56], k_{INS} is estimated to be 1%.

3.2. Aircraft Price

Since 19-seat fuel cell aircraft do not yet exist, their purchase price must be estimated from models. In this study, a similar approach is used as in the study [57]: First, the aircraft is disassembled into the following parts: wing, fuselage, landing gear, empennage, system group, payload group, and engine group. It is assumed that all parts, except the engine group, are the same for the conventional and fuel cell aircraft and that their price depends linearly on their mass [57,58]. Second, the mass of each part is determined for both the conventional and fuel cell aircraft using the procedure explained in detail in [12]. Finally, the price of each part, except engine group, is calculated as follows:

$$P_{i,f} = \frac{m_{i,f}}{m_{i,c}} \, p_{i,c} P_{A,C} \tag{3}$$

where $P_{i,f}$ is the price of the i-th part of a fuel cell aircraft, $m_{i,f}$ is the mass of the i-th part of a fuel cell aircraft, $m_{i,c}$ is the mass of the i-th part of a conventional aircraft, $p_{i,c}$ is the share of the i-th part in the manufacturing cost of a convectional aircraft, and $P_{A,C}$ is the price of the conventional aircraft. The shares of the parts in the manufacturing cost are [57]: wing 27%, fuselage 28%, empennage 10%, landing gear 3%, engines 9%, systems 6%, payload 11%, and assembly 6%.

The price of the fuel cell engine group is estimated by adding the prices of its components: fuel cell system, electric motor, and fuel cell tank. The price of fuel cell systems is decreasing and is expected to reach 40 EUR/kW in Europe by 2030 [59]. After 2030, the cost of fuel cells is not expected to decrease significantly. Prices for electric motors suitable for use in aircraft range from 62 EUR/kW to 94 EUR/kW [60]. There are also cheaper versions with shorter lifetimes, whose prices range from 26 EUR/kW to 32 EUR/kW [61]. In this study, we will consider the more expensive electric motors.

Currently, there are no commercial liquid hydrogen storage tanks on the market that can be used directly in a 19-seat hydrogen fuel cell aircraft. To this end, a small direct survey of potential manufacturers was conducted. It was found that the cost of a liquid hydrogen tank with a capacity of 7 m^3 (1 m long and 3 m in diameter), with a pressure of up to 10 bar, using vacuum insulation (MLI), with a stainless steel inner tank and a carbon steel outer tank, at an evaporation rate of 3% per day, would be 162,000 EUR or 324 EUR/kg, while the cost of a tank with 14 m^3 capacity is about 249,000 EUR or 250 EUR/kg [62]. A similar tank with 7 m^3 capacity made of aluminum would cost about 153,000 EUR or 306 EUR/kg [63]. Although the above tanks are too heavy to be used in 19-seat aircraft, it is assumed that the equivalent tanks would use similar technology, except that the evaporation rates would be much higher because they would not have to store the hydrogen for long periods. Therefore, the price of the tanks would likely be similar to those mentioned above. On the other hand, a study by [26] states that the cost of a liquid hydrogen storage system acceptable for aircraft is expected to reach values below 550 EUR/kg by 2050. Therefore, in this study, we will assume a more conservative price of a hydrogen tank of 550 EUR/kg.

The price of engine group $P_{E,f}$ is therefore calculated as

$$P_{E,f} = P_{FC} \cdot 40\,\mathrm{EUR/kW} + P_{EM} \cdot 95\,\mathrm{EUR/kW} + m_F \cdot 550\,\mathrm{EUR/kg}\,, \tag{4}$$

where P_{FC} is the power of the fuel cell system, P_{EM} is the power of the electric motor ($P_{EM} < P_{FC}$ as part of the fuel cell power is used for cooling and compression systems), and m_F is the fuel capacity of the tank. The estimation of fuel cell system power, electric motor power, and tank fuel capacity is explained in detail in [12].

3.3. Maintenance and Crew Cost

The maintenance cost (C_M) depends on the number of flight hours and can be calculated as follows:

$$C_M = (C_{mat} + C_E \cdot t_{lab}) \cdot N_{FH} \tag{5}$$

where C_{mat} is the material cost per flight hour, t_{lab} is the service time per flight hour, N_{FH} is annual number of flight hours made by aircraft, and C_E is the hourly rate of an engineer. Hourly rates for engineers in the aerospace industry vary by country and are summarized in Table 5 for the countries where the companies listed in Section 2 operate 19-seat aircraft [64]. According to [56], maintenance consists of periodic checks, revisions, lubrication, oil changes, engine overhauls, propeller overhauls, and instrument replacements. Checks, revisions, lubrication, and oil changes require 1.027 operating hours per flight hour and 5.048 EUR in materials per flight hour. Replacing engines, propellers, and instruments costs 188.91 EUR per flight hour, with materials accounting for most of the cost and labor less than 1% of the total overhaul cost. Hydrogen aircraft do not require oil changes or engine overhauls, which means that inspections, overhauls, lubrication, propeller, and instrument changes require 1.025 maintenance hours per flight hour and 33.943 EUR in material costs. In addition, the maintenance of the fuel cells, the cryogenic tank, and the electric motor overhauls have to be taken into account. The service life of electric motors can range from 30,000 to 40,000 h of operation, which means that no overhaul of the electric motor is required during the service life of the aircraft [65]. Nevertheless, some electric motors designed specifically for aircraft use may have a life span that is three times shorter, but are also about three times cheaper, which leads to the same final price [61]. In this paper, the more expensive electric motors are considered, so no overhaul of electric motors is foreseen. Cryogenic tanks are expected to be technically advanced enough that overhaul of the tanks will not be necessary during the service life of the aircraft [66]. The maintenance cost of the fuel cell system is estimated from the data on the automotive industry. The fuel cell system consists of a fuel cell stack representing 43.7%, of the fuel cell system price, and a balance of plant (BOP) representing the rest of the fuel system price [67]. The life of the fuel cell stack is estimated at 4100 operating hours, while the BOP maintenance, including replacement of valves and hoses containing rubber and nylon, humidifier, coolant pumps, thermostatic valves, and other mechanical components, is estimated at 30% of the initial BOP price for every 8000 operating hours [68]. The annual maintenance costs for fuel cells ($C_{M,FC,a}$) are therefore estimated to be

$$C_{M,FC,a} = C_{M,FC,FH} \cdot N_{FH} = \left(\frac{0.437}{4100} + \frac{0.3 \cdot 0.563}{8000} \right) C_{FC} \cdot N_{FH} = 1.277 \cdot 10^{-4} \cdot C_{FC} \cdot N_{FH} \,, \quad (6)$$

where $C_{M,FC,FH}$ is the maintenance cost of fuel cells per flight hour, N_{FH} is the number of flight hours, C_{FC} is the fuel cell system price already given in Section 3.2.

Table 5. Economic data per country: hourly rates of aircraft engineer C_E [64], pilot C_{CP} [64] and cabin crew C_{CC} [64], route unit charge k_R [69], terminal unit charge k_T [70], and price of kg of kerosene [71]. All prices are in EUR. † Iceland is not a member state of EUROCONTROL.

Country	C_E	C_{CP}	C_{CC}	k_R	k_T	$P_{F,k}$
UK	21.47	38.69	21.6	68.97	/	1.63–3.48
Iceland †	23.22	40.90	23.00	/	/	2.91
French	20.75	39.61	22.27	73.02	196.34	1.81–3.38
Portugal	12.23	23.18	13.04	42.32	158.54	2.83
Croatia	8.35	16.97	9.54	50.42	323.71	1.64–1.67
Estonia	8.79	17.01	9.56	32.74	90.72	1.4
Italy	19.08	35.67	20.06	80.11	214.89	1.75–1.93

The crew of a 19-seat aircraft consists of a pilot, a copilot, and a cabin crew member [72]. The crew members are paid by block time, including flight time and time spent on the ground between flights [51]. Crew costs (C_C) can therefore be calculated as follows:

$$C_C = (2 \cdot C_{PC} + C_{CC}) \cdot N_{BH} = (2 \cdot C_{PC} + C_{CC}) \cdot (N_{FH} + N_F \cdot t_G) \quad (7)$$

where C_{PC} is the pilot/co-pilot hourly rate, C_{CC} is the cabin crew hourly rate, N_{BH} is the annual number of block hours, N_{FH} is the annual number of flight hours, N_F is the annual number of flights, and t_G is the average time on the ground between flights. According to the OAG database [38], for Trade Air company $t_G = 0.5\,\mathrm{h}$. Hourly rates for pilots and cabin crew vary by country [64] and are summarized in Table 5 for countries where the companies listed in Section 2 operate 19-seat aircraft.

3.4. Fuel Cost

The fuel cost (C_F) is calculated as follows

$$C_F = m_f \cdot P_F\,, \tag{8}$$

where m_f is the mass of fuel consumed and P_F is the price of fuel. The mass of fuel consumed can be calculated from mission fuel fraction M_{ff}:

$$M_{ff} = \frac{MTOM - m_F}{MTOM} \qquad m_F = MTOM(1 - M_{ff})\,. \tag{9}$$

The mission fuel fraction is calculated by multiplying the mission segment mass fractions $k_i = m_i/(m_{i+1})$, where m_{i+1} is the mass at the beginning of each flight phase and m_i is the mass at the end of the flight phase:

$$M_{ff} = k_B \cdot k_C \cdot k_E \tag{10}$$

where k_B is the mass fraction at the beginning of the flight phase and includes engine start, taxi-out, takeoff, and climb; k_C is the mass fraction at cruise; and k_E is the mass fraction at the end of the flight phase and includes landing and taxi-in. Mass fractions k_B and k_E are treated as constants that depend on a type of aircraft, while k_C can be calculated using Breguet's equation for propeller aircraft:

$$k_C = e^{-R_c/B_s}\,, \qquad B_s = \frac{L}{D}\frac{\eta}{SFC_P\,g} \tag{11}$$

where SFC_P is the power-specific fuel consumption, η is the propeller efficiency, $g = 9.81\,\mathrm{m/s^2}$ is the gravitational acceleration constant, L/D is lift-to-drag ratio in cruise flight, and R_c is the distance traveled by the aircraft in cruise flight. The typical propeller efficiency is 0.8, the typical lift-to-drag ratio of a 19-seat turboprop aircraft is 18, while the specific fuel consumption of a turboprop engine is $SFC_P = 0.09 \cdot 10^{-6}\,\mathrm{kg/J}$. For fuel cell aircraft, the specific fuel consumption of the turboprop engine must be replaced by that of the fuel cell propulsion system $SFC_{Pfc} = 0.02 \cdot 10^{-6}\,\mathrm{kg/J}$ [12]. According to [58,73], for conventional turboprop aircraft $k_B = 0.97$ and $k_E = 0.985$, while for fuel cell aircraft k_B and k_E must be recalculated, taking into account the difference between the specific fuel consumption of turboprop and fuel cell propulsion systems, obtaining $k_B \cdot k_E = 0.985$ [12].

The cost of kerosene in countries where 19-seat aircraft are used and at individual Croatian airports is listed in Tables 5 and 6. The prices are taken from the portal [71].

Table 6. Airport charges and price of kerosene at Croatian airports. Charges refer to national flights and round trips during daylight.

Airport Unit	$C_{FEE,MTOM}$ EUR/Tonne	$C_{FEE,PASS}$ EUR/Pass.	$C_{FEE,U}$ EUR	$P_{F,k}$ EUR/kg
Zagreb [74]	6.38	18.35		1.69
Split [75]	6.38	9.6	89	1.67
Dubrovnik [76]	6.45	11.5		1.68
Rijeka [77]	23.1	21		1.68
Osjek [78]	6.9	9	100	1.69
Pula [79]	4	9	100	1.67

The current production cost of green hydrogen ranges from 2.8 EUR/kg to 8 EUR/kg, but it is expected to decrease in the future [80–82]. The selling price of hydrogen depends on several factors, such as the purity level of hydrogen required, distribution, the state of the hydrogen (gaseous or liquid), storage, and retail costs, and is therefore difficult to generalize. According to an expert estimate, transportation, distribution, liquefaction, storage, and sales account for between 110% and 140% of the incremental costs to the production price [83,84]. Based on [82] production cost prices and adding 110% due to transportation, distribution, liquefaction, storage, and sales costs, the hydrogen price is estimated to reach between 5.25 EUR and 9.45 EUR (average 6.56 EUR) by 2030 and between 2.1 EUR and 5.78 EUR (average 4.04 EUR) by 2050.

3.5. Fees and Charges

The air service provider pays charges to EUROCONTROL's Central Route Charges Office (CRCO) and to the airports. The Central Route Charges Office (CRCO) is a centralized system for cost recovery of air services provided by EUROCONTROL Member State operators. The CRCO collects route charges, terminal charges, and navigation charges. The route charge is calculated as follows:

$$C_{FEE,R} = k_R \frac{R}{100} \sqrt{\frac{MTOM}{50}}\,, \tag{12}$$

where $MTOM$ is the maximum takeoff mass of the aircraft in tonnes rounded to one decimal place, R is the distance between the arrival and departure airports, and k_R is the country-specific route unit charge. The terminal charge is calculated as follows:

$$C_{FEE,T} = k_T \left(\frac{MTOM}{50}\right)^{0.70} \tag{13}$$

for all Member States except Moldova and Northern Macedonia, where the terminal charge is proportional to the MTOM. The k_T is the country-specific terminal unit charge. The navigation charge is levied only by non-member countries of EUROCONTROL. The country-specific unit charges k_R and k_T are summarized in Table 5 for the countries where the companies listed in Section 2 operate 19-seat aircraft and are members of EUROCONTROL [69,70].

Airports charge various fees, including takeoff and landing fees, parking fees, passenger handling fees, security fees, ground handling fees, central infrastructure fees, and traffic handling fees. Airports also impose charges for various services provided at special request and charges for passengers with reduced mobility. Some airports do not charge all fees. Airport charges can be summarized as follows:

$$C_{FEE} = C_{FEE,U} + C_{FEE,PASS} \cdot N_p + C_{FEE,M} \cdot INT(MTOM)\,, \tag{14}$$

where N_p is the number of passengers and $INT(MTOM)$ is the MTOM of aircraft in tonnes truncated to a whole number (e.g., $INT(7.8) = 7$). $C_{FEE,PASS}$ usually includes a passenger handling charge, security charge and part of central infrastructure charge, $C_{FEE,M}$ usually includes a landing and take-off charge and part of central infrastructure charge, while $C_{FEE,U}$ usually includes part of the central infrastructure charge and the handling of the aircraft. Prices for various Croatian airports are listed in Table 6. Only the portion of the charge that depends on the MTOM differs between conventional and fuel cell aircraft, so only this portion is included in DOC, while the per-unit charge and the per-passenger charge are considered to be part of the IOC in this study. In addition, airports charge a parking fee when the aircraft overnights. Most Croatian airports charge a daily parking fee, if the stay at the airport exceeds 4 h. The annual parking fee is thus

$$C_{FEE,P,d} = 365.25 \cdot C_{P,d} \cdot INT(MTOM) \tag{15}$$

where $C_{P,d}$ is the daily unit rate. In the case of Trade Air, the aircraft overnights at Osijek Airport with a daily unit rate of 4 EUR.

In summary, assuming that all flights are round-trip, the cost of the annual fee can be calculated as follows:

$$C_{FEE} = \sum_i N_{F,i} \left(2k_R \frac{R}{100} \frac{MTOM}{50} + 2k_T \left(\frac{MTOM}{50} \right)^{0.7} + C_{FEE,M,i1} \cdot INT(MTOM) \right.$$
$$\left. + C_{FEE,M,i2} \cdot INT(MTOM) \right) + 365.25 \cdot C_{P,d} \cdot INT(MTOM)\,, \tag{16}$$

where the sum runs over all possible outbound and return flights with the same origin and destination, $N_{F,i}$ is the number of outbound and return flights with the same origin and destination, and $C_{FEE,M,i1}$ and $C_{FEE,M,i2}$ are the airport charges at origin and destination airports, respectively.

3.6. Time Development of DOC

Due to inflation, the cost of the various components of DOC will change over time according to the corresponding index rate. If we define $\Delta Y = Y - 2022$, where Y is the year in which the DOC is calculated, the unit costs discussed in the previous sections must be adjusted as follows:

$$C_Y = C_{2022}(1 + I)^{\Delta_Y}\,, \tag{17}$$

where C_Y is the cost in year Y, C_{2022} is the current cost in 2022, and I is the corresponding index rate. The corresponding index rate for C_E, C_{CP}, C_{CC}, is the labour cost index (LCI) [85], while for all other costs except fuel costs, the producer price index (PPI) [86–88] is used. The ten-year average of the labor index and the production price rate for the countries in which the 19-seat airplanes are used is given in Table 7. For jet fuel, the Platts index for Europe is used [89]. The annual Platts index is calculated from the change in the price of kerosene from 2000 to 2022 and is 31.1%. On the other hand, the price of hydrogen is expected to fall in the coming years due to technological development and market expansion. Taking into account that the expected hydrogen price will average 6.56 EUR in 2030 and 4.04 EUR in 2050, as listed in Section 3.4, the estimated annual hydrogen index rate is −2.43%. Since [82] does not include the price change in inflation, the stated hydrogen index rate must be corrected by adding the annual production price rate.

Table 7. Labor cost index (LCI) [85] and producer price index (PPI) [86–88] for European countries operating flights with 19-seat aircraft. LCI and PPI are calculated as annual averages for the years 2010 to 2020.

Country	UK	Iceland	French	Portugal	Croatia	Estonia	Italy
LCI [%]	2.26	5.91	1.3	2.04	−0.11	5.66	1.19
PPI [%]	2.0	2.86	1.35	1.23	1.31	2.16	1.46

4. Results and Discussion

The comparative analysis of direct operating costs of conventional and hydrogen fuel cell aircraft has been carried out based on flight data from the airliner Trade Air from Croatia.

For a convincing analysis, the performance characteristics of both aircraft, conventional and fuel cell, must be identical. Performance characteristics such as cruise speed, altitude, takeoff, and landing distance, and rate of climb depend solely on wing loading (ratio of $MTOM$ to wing area) and power loading (ratio of engine power to $MTOM$). Therefore, if it is assured that the power loading and wing loading of fuel cell aircraft and conventional aircraft are the same, then the above performance characteristics are also the same. This would ensure that both aircraft can fly from the same airports, maintain the same flight schedule, and have the same number of annual flight hours.

Taking this into account, the *MTOM* of fuel cell aircraft is calculated using the model described in [12]. The range of fuel cell aircraft is set at 500 km with 1960 kg payload, which is sufficient for all Trade Air flights. Other parameters used for the *MTOM* calculation follow the optimistic and pessimistic scenario aircraft settings as described in [12]. The pessimistic scenario assumed a power of 5 kW/kg for the electric motor, 2.9 kW/kg for the fuel cells, and a gravimetric tank index of 60%. The optimistic scenario, which takes into account future technical development of fuel cell aircraft components, assumed a power of 40 kW/kg for the electric motor, 4 kW/kg for the fuel cells, and a tank gravimetric index of 70%. The difference in optimistic and pessimistic scenario is therefore in the *MTOM* of fuel cell aircraft.

Figure 1 illustrates the direct operating cost movement of a 19-seater conventional aircraft and a hydrogen fuel cell aircraft from 2030 to 2050, considering the development of direct operating costs over time. The upper line of the direct operating cost for the conventional aircraft represents the level of direct operating cost considering a high annual rate of kerosene at 6%, while the lower line considers a low annual rate of 3%. For the hydrogen fuel cell aircraft, we considered a compound constant rate, which includes a negative 2.43% annual rate for hydrogen prices and a constant rate of increase in industrial product prices by manufacturers across countries. We also tested a hypothetical optimistic scenario and a pessimistic scenario, which are shown by the lower and upper line.

The point where the lines of conventional aircraft and hydrogen fuel cell aircraft intersect is called the break-even point of direct operating costs, where it will be possible to achieve the same level of direct operating costs for conventional and hydrogen fuel cell aircraft. In the case where the line of direct operating costs of a conventional aircraft is above the line of a hydrogen fuel cell aircraft, this means that the latter will have higher direct operating costs, and that from an economic perspective of considering direct operating costs, the use of a hydrogen fuel cell aircraft will make more sense than the use of a conventional aircraft.

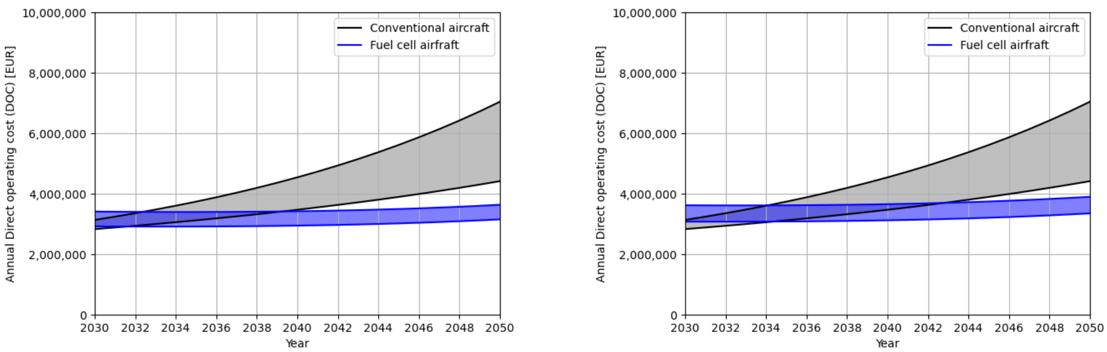

Figure 1. Annual operating cost of Trade Air: (**left**) excluding airport fees; (**right**) including airport fees.

As can be seen from Figure 2 fuel costs account for the largest share of operating costs. At this time, they account for about 45% of DOC for convection aircraft in 2023 and about 60% of DOC for fuel aircraft. The second largest portion of DOC is the cost of depreciation insurance, and interest. Since the fuel consumption and price of aircraft are closely related to the *MTOM*, the main parameters affecting DOC are therefore the *MTOM* of aircraft and the fuel price of kerosene and hydrogen. Since the price of kerosene is increasing faster than other costs over time, and at the same time the price of hydrogen and the *MTOM* of fuel cell aircraft are expected to decrease over time, this explains why the DOC of fuel cell aircraft will be lower than the DOC of kerosene aircraft in the future. The essential role of aircraft *MTOM* is clear from the difference between the optimistic and pessimistic scenarios. The fuel cell aircraft is about 4% lighter than the conventional aircraft for the optimistic scenario and about 25% heavier than conventional aircraft for pessimistic scenario.

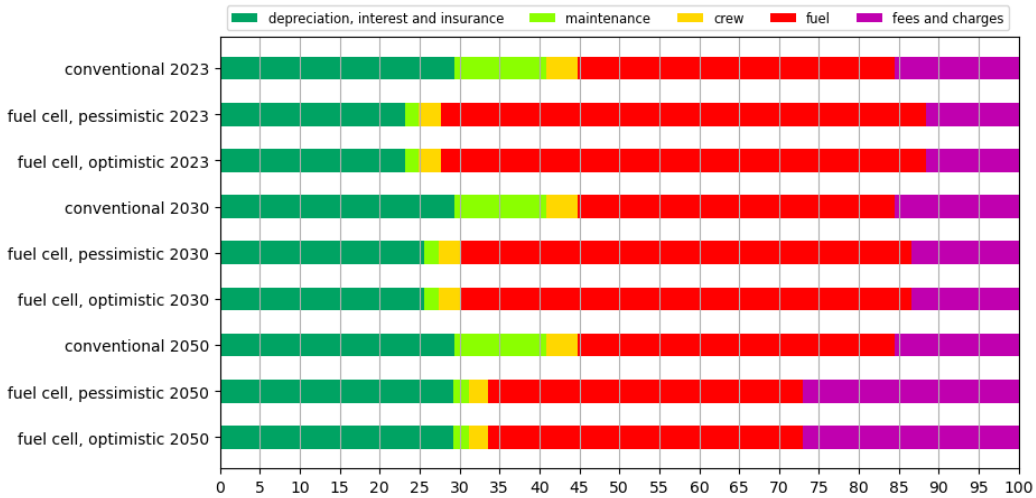

Figure 2. Breakdown of direct operating costs for the airline TradeAir.

Figure 1 shows a comparison of Trade Air's direct operating costs without airport fees on the left side and with airport fees on the right side. The analysis reveals that the direct operating costs of hydrogen fuel cell aircraft will eventually become equal to the costs of conventional aircraft (i.e., the break-even point). The biggest difference in cost levels is observed in the scenario of a low kerosene annual growth rate and the pessimistic development scenario of hydrogen fuel cell aircraft, where the cost break-even point is predicted to occur in 2039 without airport fees and in 2043 with fees. From this we can conclude that if we want to accelerate the equalization of direct operating costs of aircraft, airport fees for conventional aircraft should be increased, or fees for hydrogen fuel cell aircraft should be reduced or even eliminated. The disparity between the break-even point without considering airport fees and the break-even point considering airport fees is much smaller in the optimistic scenario. This scenario assumes the use of more powerful components in hydrogen fuel cell aircraft, resulting in a reduced weight of the aircraft. A lower weight of the hydrogen fuel cell aircraft will result in lower airport fees, which in turn will reduce the overall direct operating costs. Therefore, the airport fees for hydrogen fuel cell aircraft will be much lower in the optimistic scenario compared to the pessimistic scenario, leading to an earlier break-even point for direct operating costs. Hence, in the optimistic scenario, measures to increase the fees for conventional aircraft or decrease the fees for hydrogen fuel cell aircraft will have a lesser impact on achieving the equalization of direct operating costs of aircraft compared to the pessimistic scenario.

As shown in Figure 1 (right side), assuming a pessimistic development scenario with a low annual growth rate for kerosene, it may take until around 2042 to achieve the same level of direct operating cost while considering airport fees. However, in the case of a pessimistic scenario and a high annual growth rate for kerosene, the same level of direct operating cost may be reached by around 2034 while considering airport fees. On the other hand, if an extraordinary technological breakthrough occurs, leading to an optimistic development scenario for fuel cell aircraft, and a high annual growth rate for kerosene, the same level of direct operating cost, including airport fees, can be achieved before 2030. This suggests that a high and sustained growth in kerosene prices and a technological breakthrough leading to massive improvement in the efficiency of fuel cell aircraft could encourage the early adoption of hydrogen fuel cell aircraft due to their more favorable operating costs. While considering the constant growth rates of key parameters of direct operating costs of aircraft, we also analyzed the impact of various possible environmental measures on direct operating cost as shown in Figure 3. In the case of a mild environmental measure, we consider a surcharge on the price of kerosene of 0.171 EUR/kg in the period 2030–2050. In the case of a strict environmental measure, we consider a surcharge on the price of kerosene of 0.363 EUR/kg in the period 2030–2040 and a surcharge of 0.729 EUR/kg in the period 2040–2050. We based this on previous research that predicts different surcharges on the price of kerosene to achieve a transition to hydrogen [90].

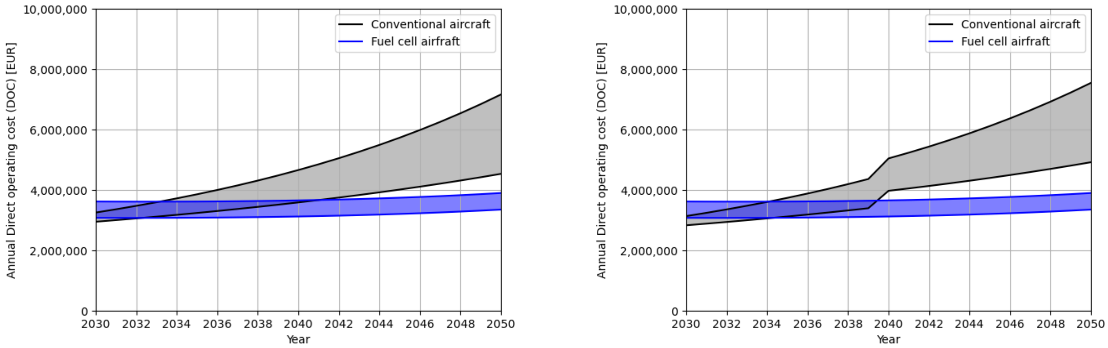

Figure 3. Annual operating cost of Trade Air: (**left**) with mild environmental measures; (**right**) with strict environmental measures.

If mild environmental policies were introduced in the form of a surcharge on the price of kerosene in an optimistic scenario, we can observe that this measure would not significantly affect the faster transition of direct operating costs to hydrogen fuel cell aircraft when used for Trade Air flights. On the other hand, strict environmental policies with higher surcharges on the price of kerosene would have a greater impact on cost transition in scenarios of low kerosene growth rates and both development scenarios. The break-even point could even be reached up to six years earlier than in the case without environmental policies. However, research suggests that if kerosene growth rates are already high and if development progresses according to an optimistic scenario, the latter alone can be a significant factor in achieving the break-even point around 2030, and policy measures may not be necessary.

5. Conclusions

Fuel cell technology in aviation is still in the process of being developed and tested. The question of whether this technology will be sufficiently interesting for use in passenger transportation remains open, particularly with regard to the costs associated with its daily operation. Direct operating costs are a crucial criterion for airliners when aquiring new aircraft. However, determining the direct operating costs of aircraft that utilize hydrogen fuel cells poses several challenges, as it is a technology that is still in the developmental stage and has yet to be fully commercialized, meaning that many technical details remain unknown or inaccessible to the public. Additionally, predicting the future poses a significant challenge as we cannot confidently predict the development of hydrogen fuel cell aircraft technology, nor the prices of kerosene and hydrogen, which in turn can impact the changes in costs over time.

The model presented in this article is specifically designed for European airlines with 19 seats. With some minor corrections, the model can be used to calculate DOC for turboprop aircraft with a different number of seats or for non-European airlines. In latter case, the calculations of fees and charges should be adjusted accordingly. Some of the parameters of the model are based on future price predictions (tanks, fuel cells) from other studies and on the prediction that the technological development and the economic situation in Europe will be similar to the last 10–20 years. If the economies of the countries change significantly, the predictions of this model would be invalid.

According to the research findings, there is a possibility that the direct operating costs of hydrogen fuel cell aircraft could fall below the direct operating costs of conventional aircraft, which may incentivize their utilization in air transportation. Kerosene prices and technological development play a crucial role in this, while environmental policy can accelerate the transition to hydrogen. Since the price development of kerosene and the technical development of fuel cell technology are global phenomena, this development can also be expected in other parts of the world and not only in European airlines.

However, the question of transitioning to hydrogen fuel cell aircraft still depends on various factors, such as technology maturity, the availability of green hydrogen at affordable prices, transportation, and environmental policies. Due to the complexity and multifaceted nature of these factors, this study cannot provide a precise answer. Nonetheless, an important conclusion was reached: with time, using 19-seat hydrogen fuel cell aircraft for air transportation could become financially feasible due to lower direct operating costs when compared to conventional aircraft.

In addition to fuel cell aircraft, turbine-hydrogen aircraft are another interesting future option as an environmentally friendly replacement for larger jet aircraft. A comparative analysis of DOC between jet aircraft and hydrogen turbine aircraft should be the next research step.

Author Contributions: Conceptualization, A.P.B.; methodology, A.P.B.; software, A.P.B.; validation, M.M.; formal analysis, A.P.B.; investigation, M.M.; data curation, M.M.; writing—original draft preparation, A.P.B.; writing—review and editing, M.M.; visualization, A.P.B.; project administration, M.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research took place within the MAHEPA project, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 723368. The article only reflects the authors' views and the European Union is not liable for any use that may be made of the information contained therein.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We wish to extend my special thanks to Tomislav Letnik from Faculty of Civil Engineering, Transportation Engineering and Architecture, University of Maribor for providing quality reading of the article and Josef Kallo, from H2FLY, for sharing their valuable experience form research and development of fuel cell hydrogen aircraft and revise the flight characteristics of turboprop fuel cell hydrogen aircraft on liquid hydrogen.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AEA	Association of European Airliners
AI	Airbus Industries
BET	Beechcraft 1900D
CRCO	Central Route Charges Office
D28	Dornier 228 NG
DLH	Lufthansa
DLR	German Aerospace Center
DHC	DHC-6 Twin Otter
DOC	direct operating cost
EU	European Union
FSH	Fairchild Swearingen Metroliner
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	internal combustion engine
IOC	indirect operating cost
J31	British Aerospace Jetstream
L410	Aircraft Industries L410 NG
LCI	Labour cost index

MTOM	Maximal take-off mass
PPI	producer price index
UK	United Kingdom

The following constants are used in manuscript:

Symbol	Definition	Value	Reference
$C_{mat,C}$	Material cost per flight hour for conv. aircraft	193.96 EUR	[56]
$C_{mat,FC}$	Material cost per flight hour for fuel cell aircraft	33.945 EUR	[56]
g	gravitational acceleration constant	9.81 m/s^2	
k_{INS}	Annual insurance rate	0.01	[54]
k_{INT}	Annual interest rate	0.05	[56]
L/D	Lift to drag ratio in cruise	18	[12]
N_{LY}	Useful life of aircraft	20 years	[53]
S_{FCP}	Power-specific fuel consumption for conv. aircraft	$0.09 \cdot 10^{-6}$ kg/J	[12]
$SFCPfc$	Power-specific fuel consumption for fuel cell aircraft	$0.02 \cdot 10^{-6}$ kg/J	[12]
$t_{lab,C}$	Service time per flight hour for conv. aircraft	1.027 h	[56]
$t_{lab,FC}$	Service time per flight hour for fuel cell aircraft	1.025 h	[56]
t_G	Average time between two flights	0.5 h	[38]
η	Propeller efficiency	0.8	[12]

The following symbols are used in manuscript:

Symbol	Definition
C_C	Annual cru cost [EUR]
C_{CC}	Cabin crew hourly rate [EUR]
C_{DEP}	Annual depreciation costs [EUR]
$C_{DOC,a}$	Annual direct operating costs [EUR]
C_E	Hourly rate of aircraft engineer [EUR]
C_{FC}	Fuell cell system price [EUR]
C_{FEE}	Annual fees and charges [EUR]
$C_{FEE,PASS}$	Part of airport charge charged per passenger [EUR]
$C_{FEE,M}$	Part of airport charge charged per tonne of MTOM [EUR]
$C_{FEE,M,i1}$	Airport charges cost at the origin airport [EUR]
$C_{FEE,M,i2}$	Airport charges cost at the destination airport [EUR]
$C_{FEE,P,d}$	Annual parking costs [EUR]
$C_{FEE,R}$	Route charge costs [EUR]
$C_{FEE,T}$	Terminal charge cost [EUR]
$C_{FEE,U}$	Part of airport charge charged per aircraft [EUR]
C_{FUEL}	Annual fuel costs [EUR]
C_F	Fuel costs [EUR]
C_{INS}	Annual insurance costs [EUR]
C_{INT}	Annual interest costs [EUR]
C_M	Annual maintenance costs [EUR]
$C_{M,FC,a}$	Annual maintenance cost of fuel cells [EUR]
$C_{M,FC,FH}$	Maintenance cost of fuel cells pef flight hour [EUR]
C_{mat}	Material cost per flight hour [EUR/h]
$C_{P,d}$	Daily unit rate for parking costs [EUR]
C_{PC}	Pilot/co-pilot hourly rate [EUR]
C_Y	Cost in year Y [EUR]
C_{2022}	Cost in 2022 [EUR]
I	Corresponding index rate (Labour index rate, Platts index, producer price index)
$INT(MTOM)$	MTOM of aircraft in tonnes truncated to a whole number (INT 7,8 = 7) [-]
k_B	Mass fraction at the beginning of the flight phase [-]
k_C	Mass fraction at cruise [-]
k_E	Mass fraction at the end of the flight phase [-]
k_i	Mission segment mass fractions [-]
k_R	Route unit charge [EUR]
k_T	Terminal unit charge [EUR]
m_F	Fuel capacity of the tank [kg]
m_f	Mass of fuel consumed during the flight [kg]

M_{ff}	Share of fuel consumed in a flight [-]
$m_{i,c}$	Mass of the i-th part of conventional aircraft [kg]
$m_{i,f}$	Mass of the i-th part of hydrogen fuel cell aircraft [kg]
$MTOM$	Maximum take- off mass [t,kg]
N_{BH}	Hourly block hours [h/year]
N_F	Annual number of flights [-]
$N_{F,i}$	Number of outbound and return flights with the same origin and destination
N_{FH}	Annual number of flight hours by aircraft [-]
N_p	Number of passengers [-]
P_A	Price of aircraft [EUR]
$P_{A,C}$	Price of conventional aircraft [EUR]
$P_{E,f}$	Price of engine group of hydrogen fuel cell aircraft [EUR]
P_{EM}	Power of electric motor [kW]
P_F	Price of fuel (kerosene or hydrogen) [EUR/kg]
P_{FC}	Power of fuel cell system [kW]
$p_{i,c}$	Share of i-th part in the manufacturing cost of a conventional aircraft [-]
$P_{i,f}$	Price of the i-th part of a fuel cell aircraft [EUR]
R	Distance between arrival and departure airports [km]
R_c	Distance travelled by aircraft in cruise flight [m]
t_{lab}	Service time per flight hour [h]

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