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Estimation of Liquid Hydrogen Fuels in Aviation

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Abstract: As the demand for alternative fuels to solve environmental problems increases worldwide due to the greenhouse gas problem, this study predicted the demand for liquid hydrogen fuel in aviation to achieve 'zero-emission flight'. The liquid hydrogen fuel models of an aircraft and all aviation sectors were produced based on the prediction of aviation fleet growth through the classification of currently operated aircraft. Using these models, the required amount of liquid hydrogen fuel and the total cost of liquid hydrogen were also calculated when various environmental regulations were satisfied. As a result, it was found to be necessary to convert approximately 66% to 100% of all aircraft from existing aircraft to liquid hydrogen aircraft in 2050, according to regulations. The annual liquid hydrogen cost was 4.7–5.2 times higher in the beginning due to the high production cost, but after 2030, it will be maintained at almost the same price, and it was found that the cost was rather low compared to jet fuel.

Keywords: liquid hydrogen; aviation fuel; carbon neutral; zero-emission flight; liquid hydrogen-fueled aircraft

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1. Introduction

In the case of aircraft, conventional jet fuel from crude oil is used, and global warming and climate change are continuously increasing according to the increase in the total fuel consumption and emissions of greenhouse gases. In aviation, CO_2 (carbon dioxide) emissions account for 2.6% of annual emissions [1,2] and show an annual growth rate of 4.5–4.8% [3,4], which is expected to continue.

Due to these problems, regulations to reduce pollutants are being strengthened worldwide to reduce greenhouse gases and global warming according to the Paris Agreement [5]. The ICAO (International Civil Aviation Organization) has achieved carbon-neutral growth since 2020 (CNG 2020) [6], and IATA (International Air Transport Association) aims to reduce its CO_2 emissions by 50% by 2050 [7]. To achieve this goal, an international aviation carbon offset and reduction system called CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) was proposed as a countermeasure [8]. In particular, in aviation, CO_2 should be reduced by 75% and NOx by 90% by 2050 compared to 2000 according to the Flightpath 2050 commitment [9].

As such, regulations are being implemented around the world, and there is an increasing demand for the use of eco-friendly alternative fuels, such as LNG (Liquefied Natural Gas), instead of the conventional Jet-A fuel to solve environmental problems [10]; 'Zero-emission flight' demand is also increasing. Reducing CO_2 emissions may include improved airframes or engines, efficient ground operations, and the use of alternative fuels [11–14]. As an alternative to the environmental impact and exhaustion of existing fuels, many studies have been conducted on various alternatives, such as biofuel, ammonia, and hydrogen [15–18]. However, hydrogen is attracting attention as a true zero-carbon fuel [16].

Hydrogen has approximately 3 times higher specific energy than conventional fuels and 11 times lower specific density than conventional fuels [17,19]. Additionally, since it does not contain carbon, there are no CO_2 emissions, and no by-products, such as SOx, are generated. Many hydrogen-fueled projects, such as B-57B, TU-155, and Phantom eye, have been produced, and projects for their application to commercial planes, such as Cryoplane, have also been carried out [20]. Airbus has released a concept design for a hydrogen-powered zero-emission flight code named "ZEROe", which will be put into service in 2035 [21].

The need for hydrogen has been mentioned in several existing studies, and the demand for hydrogen is increasing in the aviation field, but we are facing the problem of constructing infrastructure for it. It is therefore necessary to estimate the capacity of the required fuel, and a model for hydrogen fuel estimation is needed. Several studies have mentioned whether hydrogen can be used as an aviation fuel by comparing it with other fuels [16] and have made predictions about the amount of fuel consumed or required for hydrogen-fueled aircraft [22,23]. However, these were about a specific type of aircraft, not the entire aviation sector, or they were for a new type of aircraft is being made and predicted, so fuel estimation from the overall transportation perspective is necessary, such as the global fuel estimation study of Jet A fuel [24] by Seymour et al. In [24], for fuel estimation in air transportation, aircraft type, and airport origin-destination information were used. In addition, simulation was conducted for the entire flight profile using EUROCONTROL's aircraft performance model.

In this study, the total required amount of liquid hydrogen fuel was calculated by predicting the amount of hydrogen fuel used in aviation by aircraft type. In short, hydrogen will be used as fuel to solve environmental problems, and operational infrastructure is required to operate hydrogen-fueled aircraft in the aviation sector. Using the results of this study to estimate the total required amount of liquid hydrogen fuel will help build infrastructure.

Section 2 lists the necessity of hydrogen fuel for aviation through environmental regulations, alternative fuels, and examples of hydrogen-fueled aircraft. Section 3 presents the LH_2 fuel model based on the frequency of aircraft use and Jet A fuel as a method for estimating hydrogen fuel requirements. Finally, in Section 4, the required amount of hydrogen fuel was estimated based on the model presented above, and in Section 5, a conclusion is drawn.

2. LH_2 as an Aviation Fuel

2.1. Climate Regulations

There is a large amount of concern surrounding the problems of greenhouse gases and global warming around the world, and to solve these problems, the Kyoto Protocol in 1997 tried to stabilize the concentration of greenhouse gases in the atmosphere to a level that would not have a dangerous effect. However, there was no mention of the extent to which it was stabilized, and no binding force was established. In the 2015 United Nations Framework Convention on Climate Change, we worked to keep the global average temperature below 2 degrees Celsius compared to pre-industrial levels and further limit the temperature rise to 1.5 degrees or less. This led to the Paris Agreement, an international agreement to carry out this action [15].

CO_2 emissions from the global aviation industry account for 2% of the total anthropogenic CO_2 emissions and 12% of all transport sources [1,2]. Aviation traffic is expected to increase by 4.0~4.3% every year continuously; thus, it is necessary to reduce CO_2 emissions accordingly [3,4]. IATA, ATAG (Air Transport Action Group), etc., set the cap on CO_2 emission for carbon-neutral growth from 2020 and are trying to reduce it to 50% of the 2005 level by 2050 [6,7]; ACARE (The Advisory Council for Aeronautical Research in Europe) has set targets to reduce the fuel consumption rate of new airplanes by 50% and reduce NOx emissions by 80% after 2020 [25].

The European Union estimates that by 2050 through Flightpath 2050, a 75% reduction in CO_2 emissions and a 90% reduction in NOx emissions will be possible [9]. ICAO has established CNG 2020 (carbon neutral growth from 2020) to stabilize the level of CO_2 emission after 2020. Through CORSIA, a carbon offset and reduction plan was developed to reduce CO_2 emissions from international flights [8]. As such, CO_2 emissions are increasing in the aviation sector, and global efforts to reduce them are continuing.

2.2. LH_2 as a Fuel

As shown in Section 2.1, in the aviation field, methods to improve aerodynamics—new engine architecture, aircraft systems, novel airframes, structure, and materials [1,26] to reduce CO_2 emissions and low-carbon energy from existing hydrocarbon-based kerosene fuels methods, such as changing to sustainable alternative jet fuels [10,16]—are in progress. However, there is a limit to reducing emissions through structural changes [26,27], so aircraft manufacturers are focusing on developing new aircraft using alternative fuels.

ICAO presents innovative fuel concepts that can help the environment by dividing them into Sustainable Aviation Fuels (SAFs), Lower Carbon Aviation Fuels (LCAFs), and hydrogen. Various alternatives to the existing kerosene Jet A fuel have been proposed: biofuel made from vegetable oil, animal fat, sugar cane, etc. [18], and a low-carbon cryogenic fuel, LNG, and liquid hydrogen with no CO_2 emissions [15,16], among others.

Figure 1 shows aircraft classification according to CO_2 emissions in Roland Berger (2020) [25]. To reduce CO_2 emissions, the shape of the aircraft must be gradually transformed into SAFs, hybrid-electric, and battery electric in the evolution of aircraft such as increased efficiency or operational improvement, and at the end of the final change, hydrogen is used as fuel.

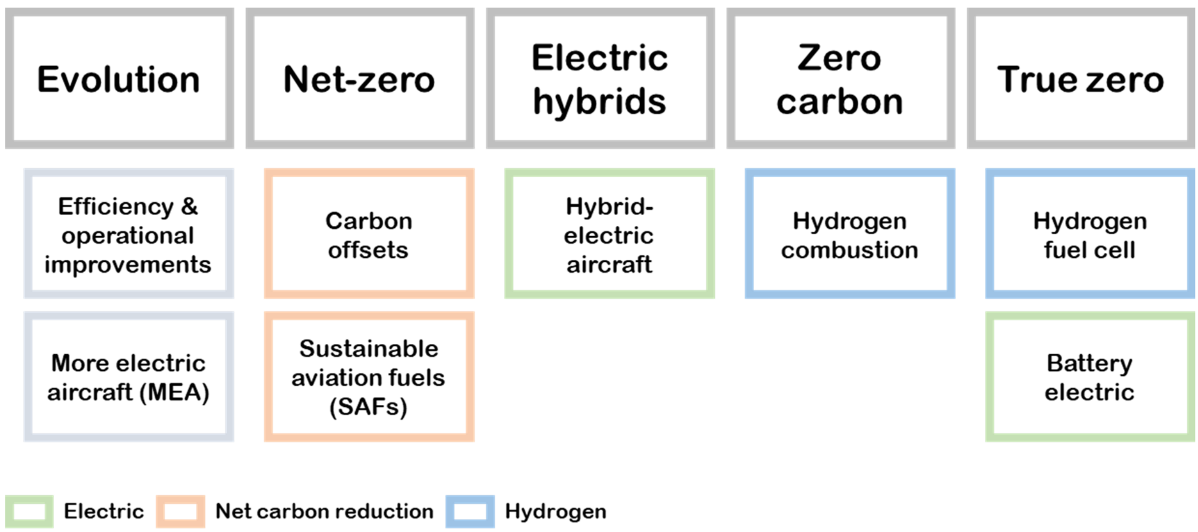

Figure 1. Aircraft classification according to carbon emissions [28].

According to the Paris Agreement, it was determined that efforts should be made to achieve "below 2 °C above pre-industrial levels" and "1.5 °C above pre-industrial level" [5]. To achieve the policy of CNG 2020, as well as to reduce the total CO_2 emissions, to become 'Zero-carbon' or 'True-zero' rather than 'Net-zero', the fuel itself should not contain carbon, e.g., biofuel or LNG. In this case, hydrogen with a zero-carbon content should be used [28].

Hydrogen can be stored in gas or liquid form. However, in the case of gas, high-pressure tanks of 350–700 bar are generally required, and the volumetric efficiency is low, so it is stored in liquid form at a cryogenic temperature of 20 K. LH_2 (liquid hydrogen) has a specific energy that is 2.8 times higher than that of conventional jet fuel and has a specific density that is approximately 11 times less than that of conventional jet fuel [17,19]. According to M. Janic (2008), an aircraft using LH_2 requires 4.3 times the fuel tank to generate the same energy [17]. However, it is expected that the increased empty weight can be compensated by the low LH_2 weight, which decreases the aircraft's maximum take-off weight [22,23].

2.3. LH_2 Fueled Aircraft

Figure 2 shows the conceptual diagram of two propulsion systems using hydrogen. In many studies, as shown in Figure 2, hydrogen combustion and fuel cell aircraft have been suggested as hydrogen propulsion systems using liquid hydrogen [17,19,22,23,28]. Concerning fuel cell technology, studies are being conducted to provide power to the aircraft [29–31].

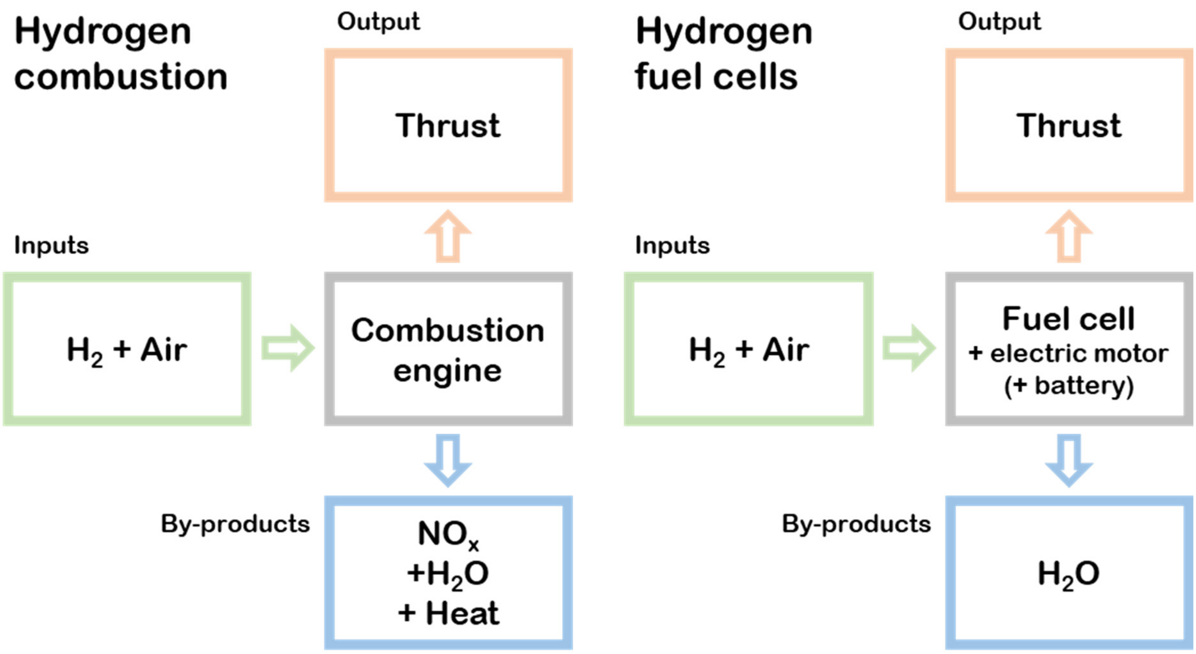

Figure 2. Propulsion system using hydrogen [28].

For the application of the hydrogen fuel cell to the aircraft, the auxiliary power unit of the Airbus A320 ATRA, a research aircraft operated by DLR in 2008, was replaced with a 20 kW fuel cell to observe the capabilities of the system [32]. In 2009, the Antares DLR-H2 successfully tested a 100% hydrogen-fuel-cell-powered aircraft [33], and in 2016, DLR developed the HY4, the world's first hydrogen fuel cell-powered passenger aircraft using a 48 kW fuel cell [34,35].

However, compared to a hydrogen combustion aircraft, when a fuel cell is used, there are many technical areas to be developed, such as the low energy density of the battery that can store energy, the power density of the fuel cell, and the output of the electric motor. Most aircraft are small and short-range [31,35]. A computer predicted that an aircraft using a hydrogen fuel cell can only operate in a short range [35].

As of 2020, more than half of the global fleet was short- and medium-range aircraft, such as B737 or A320, and the share of CO_2 emissions emitted by these aircraft is 67%. These should be replaced, however, with current fuel cell technology; the need for hydrogen propulsion aircraft using hydrogen turbines has been raised to replace aircraft in this range [35].

LH_2 as a fuel is not a new technology, and in 1957, the "B-57B Project Bee", which converted one of the Martin B-57 bomber's engines to running on hydrogen to test the propulsion of liquid hydrogen, was "the world's first hydrogen-powered airplane". Through this B-57B, it was confirmed that the LH_2 can be used for aviation. Thanks to this success, Lockheed conducted a feasibility study on the L-1011 Freighter using the LH_2, which can carry 48,230 kg of cargo. The Soviet Union modified the engine on the right side of the existing Tupolev Tu-154 airliner to operate as an LH_2 to examine the possibility of using hydrogen as an aviation fuel for economic reasons. The Tupolev Tu-155, capable of propulsion with LH_2, was first demonstrated in 1988, and it can be seen as "the first hydrogen-powered passenger aircraft" [28,36]. In addition, according to the European Commission, "CRYOPLANE", a system analysis project for liquid hydrogen-fueled aircraft in 2000 [22], and Phantom Eye [36], a high-altitude and long-endurance unmanned aircraft system in 2012, used LH_2 as aviation fuel. Various studies and experiments have been carried out in advance.

Recently, Airbus, a leading aircraft manufacturer, announced that it would use hydrogen as future aviation fuel in consideration of the environment and that it would manufacture and operate a hydrogen-powered zero-emission flight by 2035 [21].

3. Method for LH_2 Fuel Demand Estimation

Currently, there is almost no hydrogen-related infrastructure in the world, and research and investigations are being conducted on the use of hydrogen in passenger transport buses and airport vehicles at some airports and the construction of hydrogen stations for this [37]. To enter the future hydrogen society, it is necessary to construct hydrogen infrastructure, such as hydrogen airports, fueling trucks, and fuel storage tanks to use hydrogen as a fuel, and for this, it is necessary to estimate the future hydrogen consumption and demand. For this, an "LH_2 fuel estimation model" is required.

In this study, for LH_2 fuel estimation, an aircraft hydrogen fuel estimation model for each aircraft classification was created based on current aviation fuel consumption and future aviation fleet growth prediction. A future liquid hydrogen fuel demand estimation model was produced using this model.

3.1. Predicting the Frequency of Use of Aircraft

Overall aviation average traffic growth is expected to increase by 4.0~4.3% per year [1–4]. The current usage of representative aircraft models can be estimated through the classification based on the number of existing global fleets, and how much global fleet each narrow-body/wide-body/regional jet will occupy can be predicted according to future aircraft demand trends. Aircraft can be divided into narrow-body/wide-body/regional jets according to the PAX and flight range.

According to Oliver Wyman's "global fleet and MRO market forecast" [38], regional jets and turboprops account for approximately 20% of the total global fleet; narrow-body aircraft of models such as A320 or B737 account for approximately 60%; it is said that wide-body aircraft, such as Airbus's A330, A350, and A380, or Boeing's B777, B787, and B747, has a market share of approximately 20%. The narrow body market, which occupied most of the market share in 2018, will increase. On the other hand, the wide-body market is maintained at approximately 20%, and the regional jet and turboprop markets are gradually decreasing and are expected to reach approximately 7~10% in 2031. For detailed market share forecasts, refer to Table 1.

Table 1. Market share by aircraft category [38].

Year	**2017**	**2018**	**2019**	**2020**	**2021**
Narrow body	56%	57%	58%	58%	60%
Widebody	20%	20%	20%	20%	19%
Regional jet	13%	13%	13%	12%	12%
Turboprop	11%	10%	9%	9%	9%
Year	**2027**	**2028**	**2029**	**2030**	**2031**
Narrow body	65%	66%	66%	68%	65%
Widebody	21%	19%	21%	20%	19%
Regional jet	8%	8%	8%	7%	10%
Turboprop	6%	6%	5%	5%	7%

According to the World Airliner Census [39], when looking at the operating share of each aircraft as of 2019, in the narrow body market, the B737 occupies approximately 45%, the A320 occupies approximately 30%, and in the wide-body market, the B777 occupies 26%, the A330 accounts for 26%, and the B787 accounts for 15%. In regional jets, E175 accounted for 17%; the E190, 14%; the CRJ 100/200, 14%; and the CRJ 900, 13%.

The frequency of use of all aircraft was predicted through the fleet occupancy according to the aircraft classification based on previous predictions and statistics and the detailed operation share of each aircraft. Then, based on the operating share, representative aircraft of each aircraft category were selected.

- Narrow body: B737, A320, and A321;
- Wide body: B777, A330, B787, and A350;
- Regional jet: E175, E190, CRJ100/200, and CRJ900.

3.2. Jet A Fuel-Based Model for Each Aircraft

For an aircraft, the taxi-out–take-off–climb-out process during take-off from the airport and the approach–landing–taxi-in process during landing constitutes the LTO (Landing and Take-Off) cycle. The CCD (Climb, Cruise, and Descent) cycle can be divided into two stages: the cruise from the ground to the landing site and the process of the descent to the landing altitude by lowering the altitude to 3000 ft, as shown in Figure 3.

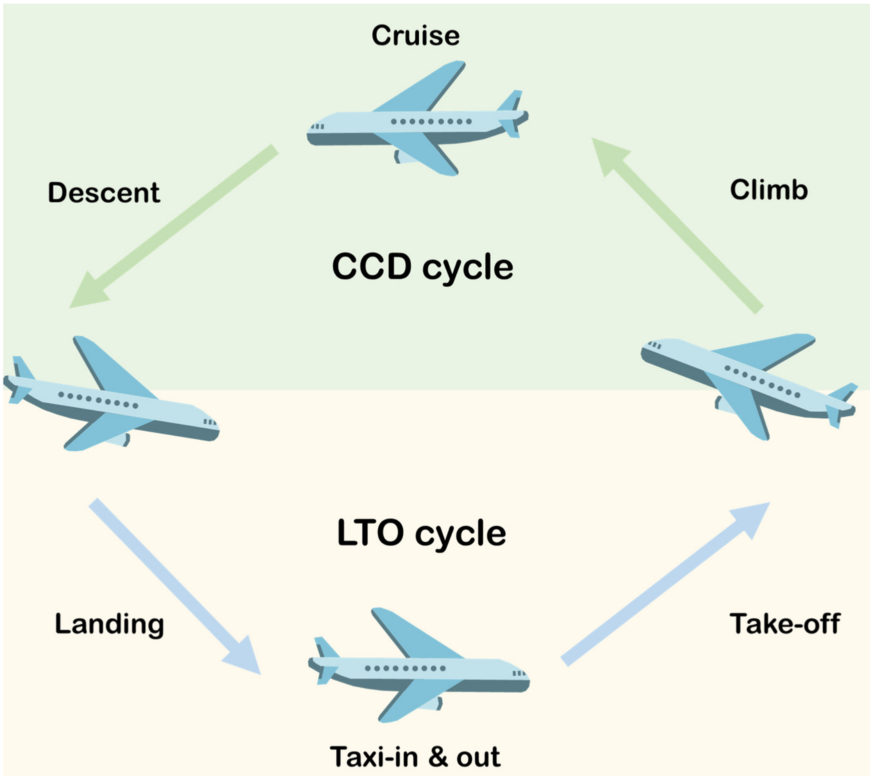

Figure 3. LTO and CCD flight phase cycle.

Aircraft fuel refers to the total amount of fuel used in all these stages, and at this time, the required fuel is estimated based on jet A through the EMEP/EEA method in this chapter as in Equation (1) [39].

$$m_{fuel} = m_{LTO} + m_{CCD} + m_{additional} \quad (1)$$

The LTO cycle differs depending on each airport's flight operations or busyness. In general, the fuel consumption is estimated using the time suggested by the ICAO: take-off

(0.7 min), climb (2.2 min), approach (4 min), taxi (26 min). Except for in a few places, on average, this consumes less time than the ICAO standard [40]. Therefore, the fuel required for the LTO cycle was estimated according to the thrust setting of the engine used for each aircraft based on the ICAO standard.

In the CCD cycle, the amount of fuel consumed or required varies according to aircraft type, the engine used, and the flight distance of the aircraft. In this study, the amount of fuel required in the CCD cycle was estimated according to the method suggested by EMEP/EEA [40], and the 'most commonly used engine' model was used for the aircraft engine. Figure 4 shows the jet fuel consumption according to the aircraft type and distance obtained through the EMEP/EEA method. Each aircraft's jet fuel consumption is expressed using a fifth-order function as in Equation (2).

$$m_{i,JetA}(s) = a_{1,i}s^5 + a_{2,i}s^4 + a_{3,i}s^3 + a_{4,i}s^2 + a_{5,i}s + a_{6,i} \quad (2)$$

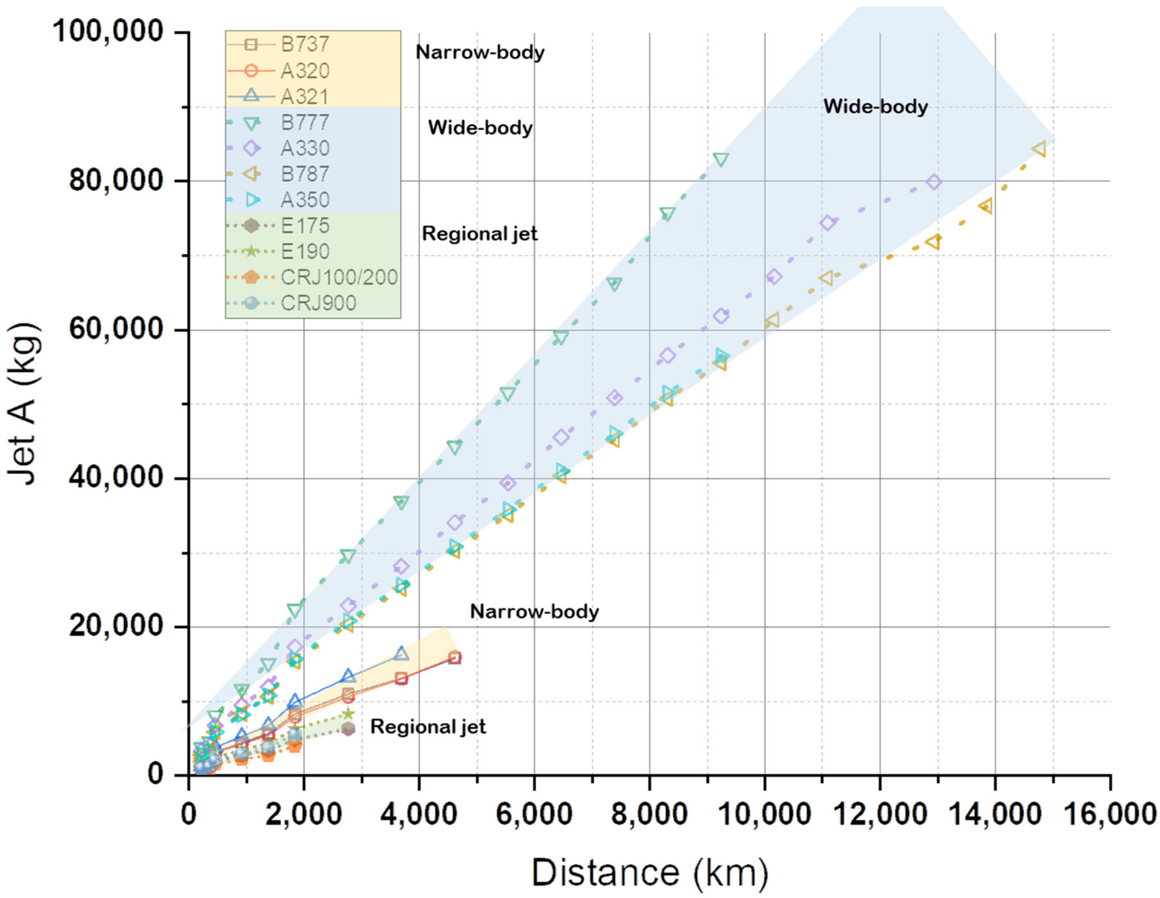

Figure 4. Jet fuel consumption depends on aircraft type and distance [40].

3.3. LH_2-Based Fuel Conversion Model for Each Aircraft

Jet A-based fuel model was manufactured as a fifth-order function as in Equation (2) using the EMEP/EEA method. The fuel model of the LH_2 aircraft was estimated based on the fuel energy content of the Jet A-based fuel model manufactured in 3.2. According to previous studies, energy consumption may increase by 9–14% depending on the type of aircraft [22]. In addition, it is known that engine efficiency can be improved by approximately 7% over 10 years based on the Jet A engine [41,42]. In the case of the hydrogen engine, it is assumed that the engine efficiency is capable of a similar rate of improvement.

Based on the fuel energy content, the amount of LH_2 equivalent to the existing 1 kg Jet A can be obtained through the following formula (Equation (3)):

$$m_{LH_2} = m_{JetA} \frac{E_{JetA}}{E_{LH_2}} \frac{\eta_{JetA}}{\eta_{LH_2}} \tag{3}$$

In general, 0.36 kg LH_2 was required as the amount of LH_2 to produce the fuel energy content of 1 kg Jet A, but it will have a lower value than this if the engine's efficiency is considered. In addition, if the change in engine efficiency with time is considered, the fuel energy content value of LH_2 will also change as a function of time. Based on the LH_2 equivalent amount of Jet A fuel, Equation (4), which reflects the efficiency that changes over time, is substituted into the previous jet A-based fuel model Equation (2) to determine the final amount of LH_2 fuel required for each aircraft can be obtained.

$$m_{i,LH_2}(s,t) = m_{i,JetA}(s) \frac{E_{JetA}}{E_{LH_2}} \frac{\eta_{JetA}(t)}{\eta_{LH_2}(t)} \tag{4}$$

$$m_{i,LH_2}(s,t) = a'_{1,i}(t)s^5 + a'_{2,i}(t)s^4 + a'_{3,i}(t)s^3 + a'_{4,i}(t)s^2 + a'_{5,i}(t)s + a'_{6,i}(t) \tag{5}$$

$$a'_{k,i}(t) = a_{k,i} \frac{E_{JetA}}{E_{LH_2}} \frac{\eta_{JetA}(t)}{\eta_{LH_2}(t)}, k = 1, \cdots, 6 \tag{6}$$

3.4. Total LH_2 Fuel Demand Estimation Model

Through the procedure from Section 3.2 to Section 3.3, the LH_2 fuel model for each representative aircraft model was calculated, as shown in Equations (4)–(6). Using this equation with the occupancy rate of the aircraft classification in 3.1, the entire LH_2 aircraft fuel demand estimation model can be calculated as shown in Equation (7).

$$\begin{aligned} m_{total,LH_2}(t) = \phi_N(t)\sum_i \phi_i(t) \cdot m_{i,LH_2}(s_N,t) \\ +\phi_W(t)\sum_i \phi_i(t) \cdot m_{i,LH_2}(s_W,t) \\ +\phi_R(t)\sum_i \phi_i(t) \cdot m_{i,LH_2}(s_E,t) \end{aligned} \tag{7}$$

The weight of LH_2 fuel consumed when flying in the range of each aircraft was estimated and using this weight, the total required LH_2 fuel demand was calculated using the classification of narrow-body/wide-body/regional jet aircraft and the occupancy of each aircraft. Aircraft flight occupancy was calculated by comparing the number of target aircraft to the number of aircraft operating within the same category and applied to the representative model of narrow-body/wide-body/regional aircraft set in Section 3.1. For the flight range, the average value of each aircraft classification was used [43].

4. Case Study

In Section 4, case studies on various cases are described using the LH_2 fuel demand estimation model presented in Section 3.

4.1. Jet A Fuel Estimation

In Section 4.1, for the verification of the fuel estimation model presented in Section 3, the annual demand for Jet A fuel was used for comparison. It was not easy to determine the required amount of Jet A fuel worldwide and based on the amount of CO_2 estimated from various references. The calculation method was used by inversely estimating the consumption of Jet A fuel. A comparative analysis was performed based on the OAG flight movement 2018 value [24] and the CO_2 emissions suggested by IATA and ICCT [43].

4.2. Carbon Neutral Growth (CNG) 2020, ATAG (50% Reduction) and Flightpath 2050 (75% Reduction)

Section 4.2 describes the calculation of the required amount of LH_2 fuel when satisfying various environmental regulations using the suggested fuel estimation model. To combine the Paris Agreement with CNG 2020, which maintains the CO_2 emissions in 2020, the IATA proposes a 50% reduction plan of the CO_2 emissions in 2005 by 2050. We analyzed how much LH_2 fuel is required by applying the "Flightpath 2050" 75% reduction plan.

First, based on the 2018 values calculated for the comparison in Section 4.1, the CO_2 emission in 2020 was estimated to be approximately 838 Mt CO_2. Based on this value, Jet A fuel, which should be reduced from 2020 to 2050, was estimated, and the conversion rate from the conventional airplane to the airplane using LH_2 fuel was estimated using this value.

Second, the aircraft conversion rate to satisfy the Paris Agreement regulations was estimated. Compared to the previous CNG 2020, IATA and Flightpath 2050 aim to reduce CO_2 emissions by 50% and 75%, respectively, in 2050 compared to the CO_2 emissions in 2005. The CO_2 emissions in 2005 were set at 650 Mt based on the "Aviation & Climate Change Fact Sheet" data [44].

4.3. LH_2 Fuel Estimation and LH_2 Price Sensitivity Analysis

Section 4.3 describes the estimation of the LH_2 fuel demand converted to a 100% LH_2-fueled airplane. Based on 2018, fluctuations and requirements were estimated from 2020 to 2050, and a comparative analysis was performed on the rate of change according to each aircraft category when the conversion from Jet A fuel to LH_2 fuel was carried out.

Currently, when using LH_2 as fuel compared to Jet A, the necessary infrastructure is not built, so it is necessary to estimate the annual demand. Based on this, the capacity of the infrastructure can also be estimated. Jet A fuel and LH_2 fuel production and supply prices are constantly fluctuating, and the total cost of each can be obtained through Equations (8) and (9). The combined effect of these was also analyzed.

$$C_{JetA}(t) = c_{JetA}(t) \times m_{total,JetA}(t) \quad (8)$$

$$\begin{aligned} C_{LH2}(t) &= c_{LH2}(t) \times m_{total,LH2}(t) \\ &= C_{JetA}(t) \frac{E_{JetA}}{E_{LH_2}} \frac{\eta_{JetA}(t)}{\eta_{LH_2}(t)} \frac{c_{LH2}(t)}{c_{JetA}(t)} \end{aligned} \quad (9)$$

Figure 5a is a graph showing the price change in jet fuel from 1990 to 2022. It is difficult to predict the price of jet fuel until 2050 because the price fluctuates for each specific event, so the price increase from 1990 to 2022 was expressed using a linearized function. This allowed for the estimation of jet fuel prices up to the year 2050.

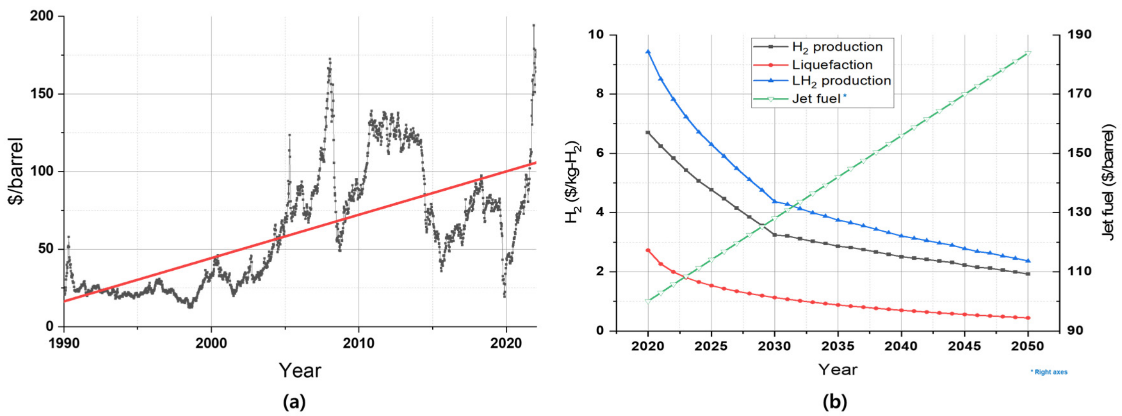

Figure 5. (**a**) Jet fuel price trend [45] and (**b**) forecast of Jet A fuel and LH_2 fuel price [46].

To liquefy hydrogen, a liquefaction plant is required, but in the case of an installed and operating plant, LH_2 production is tiny, so it is currently understood that approximately USD 2.5~3.0 per kg is needed [46–48]. However, if the liquefaction cycle is changed or a large-scale liquefaction plant is built, it has been announced that it is possible to reduce the cost by up to 50% compared to the current small scale. In light of this, in this study, the liquefaction process cost was estimated in terms of the H_2 production cost so that the cost could be reduced by up to 50% in 2050 and reflected as the LH_2 production cost.

Figure 5b shows the estimated jet fuel price from 2020 to 2050, the H_2 production cost, and the LH_2 price that reflects the liquefaction cost. The predicted values were based on the production cost of H_2, and based on these estimated values, sensitivity analysis was performed according to changes in jet fuel and LH_2 fuel prices.

5. Results and Discussion

5.1. Jet A Fuel

Section 3 describes the estimation of the CO_2 emissions and the required amount of Jet A fuel, as shown in Figure 6. It was estimated that 771 Mt CO_2 would be emitted as of 2018, which had an error within 5–10% of 812–848 Mt CO_2 presented by OAG, IATA, and ICCT, as shown in Table 2. It was found that a difference of approximately 5% of the estimate occurred depending on the method of estimating the CO_2 emission for each institution, and it was found that the 5~10% error was within a reasonable range.

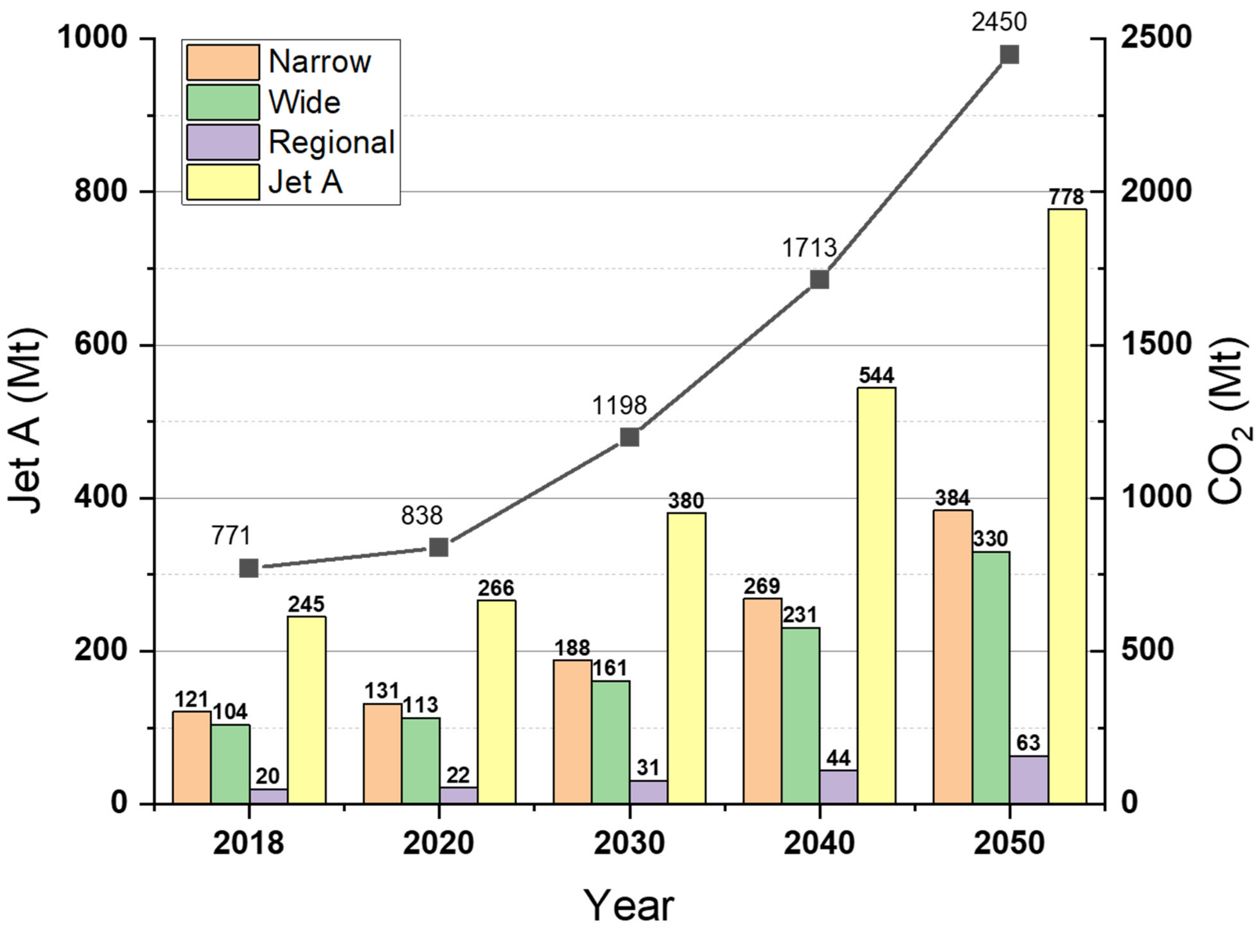

Figure 6. Total Jet A fuel demand and CO_2 emission estimation for aviation.

Table 2. CO_2 emissions and Jet A fuel estimated data.

Reference	CO_2 Emissions	Jet A Fuel (Estimated)
OAG flight movements (2018) [24]	812 Mt	257 Mt
IATA	833 Mt	263 Mt
ICCT [43]	848 Mt	268 Mt

When the demand for Jet A fuel was estimated based on the calculated CO_2 emissions, it was predicted to increase from 1.26 times to 3.17 times from 2020 to 2050 according to the increase in the air transport volume. It is predicted that the value will increase by 3.7 times compared to 2018 and approximately three times compared to 2020. It can be seen that the increasing trend according to the classification of aircraft is also approximately 3.15 to 3.17 times.

5.2. Aircraft Conversion Rate and LH2 Fuel Requirement

5.2.1. CNG 2020

As shown in Figure 7, the annual demand for Jet A fuel fluctuates according to the air transport increase, and the CO_2 emission also increases. For CNG 2020, maintaining the net CO_2 emission based on the 2020 CO_2 emission is a major goal. However, CO_2 emissions are also rapidly increasing, and CO_2 emissions are expected to be doubled in 2040 and 3 times higher in 2050 compared to 2020. To meet CNG 2020, a large amount of CO_2 reduction is required. Jet A fuel, which contributes significant CO_2 emissions, also needs to be reduced and swapped for alternative fuel in line with this trend, and the conversion is shown in Table 3.

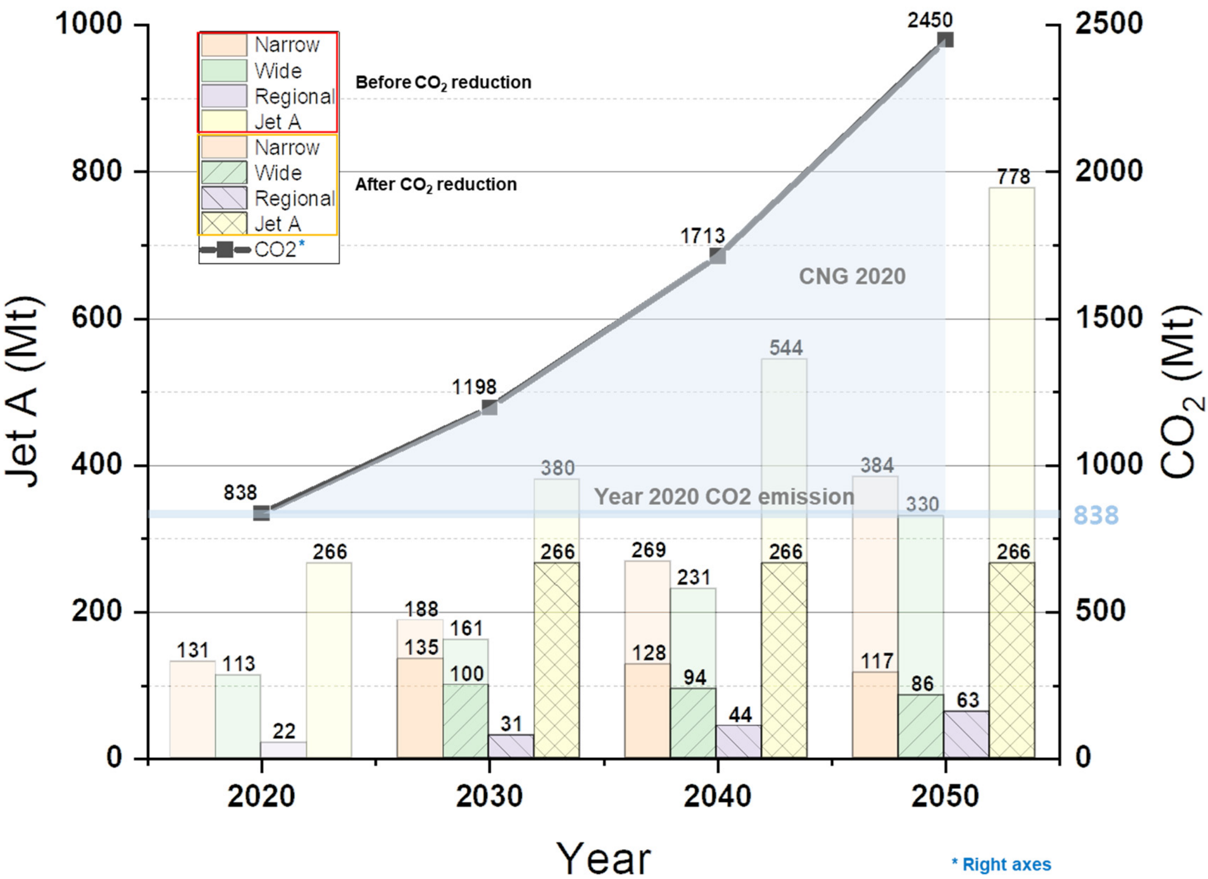

Figure 7. Total Jet A fuel conversion to LH_2 to meet CNG 2020.

Table 3. CO_2 and Jet A fuel reduction.

Year	2018	2020	2030	2040	2050
CO_2 emission	771 Mt	838 Mt	1198 Mt	1713 Mt	2450 Mt
CO_2 emission reduction	-	-	360 Mt	875 Mt	1612 Mt
Jet A fuel	245 Mt	266 Mt	380 Mt	544 Mt	778 Mt
Jet A fuel reduction	-	-	114 Mt	278 Mt	512 Mt
Transition ratio			30.1%	51.1%	65.8%

For the estimation, the ratio of narrow- to wide-body jets in 2020 was maintained. It was assumed that regional jets do not change because the absolute amount of CO_2 emitted per aircraft is smaller than that of narrow- or wide-body jets, so the effect of conversion is small. Therefore, a reduction in the use of 114 Mt Jet A is required by 2030, and a reduction in the use of 512 Mt Jet A is required by 2050. By calculating the conversion rate based on the calculated Jet A fuel reduction requirement, it is concluded that approximately 30% of aircraft in 2030, 51% in 2040, and 66% in 2050 can be converted to achieve the CNG 2020 standard when regulations are satisfied.

5.2.2. IATA/Flightpath 2050

Next, analysis was performed on IATA and Flightpath 2050 for a practical reduction policy rather than a net-zero CO_2 policy such as CNG 2020. Figure 8 shows the reduction level of Jet A fuel required to reduce CO_2 emissions by 50% and 75% in 2050, respectively, based on the 2005 650 Mt CO_2 emissions. For 2050, it is difficult to convert the entire reduction at once, so the amount of reduction for each year was estimated with the goal of a gradual reduction.

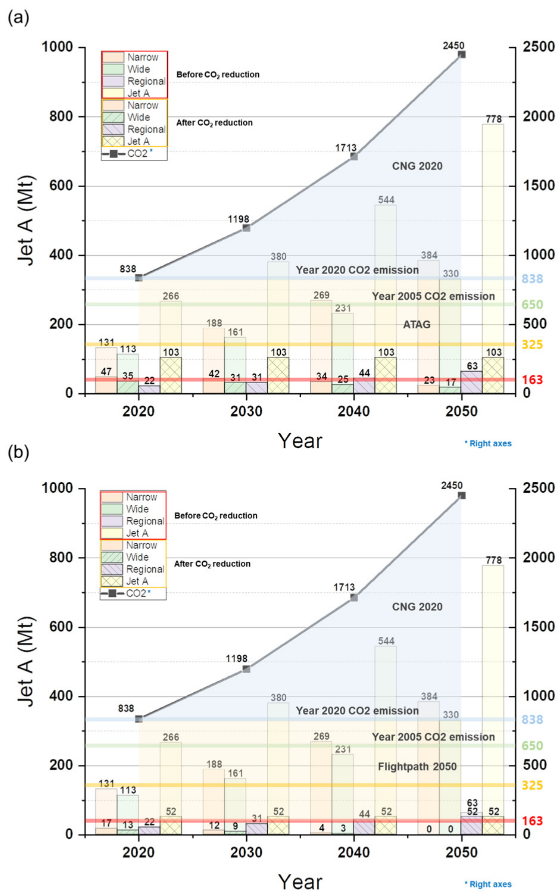

Figure 8. Total Jet A fuel conversion to LH_2 to meet (**a**) ATAG and (**b**) Flightpath 2050.

According to IATA, the 50% reduction is shown in Figure 8a. To achieve these standards, the CO_2 emission must be adjusted to 325 Mt CO_2 and the Jet A fuel to approximately 103 Mt, which is 13.2 of the estimated 2050 Jet A fuel demand. A reduction of approximately 87% is required. The use of narrow- and wide-body aircraft, which are the most frequently used, should be reduced to 5.9% and 5%, respectively, and the remaining 94~95% of aircraft use needs to be replaced with aircraft using LH_2. As in the previous section, the regional jet has little effect at the time of conversion, and the usage of Jet A fuel is 30% compared to wide-body jets and 16% for narrow-body jets. Overall, approximately 60% conversion is required in 2020, 70% in 2030, and 80% in 2040.

The 75% reduction according to flightpath 2050 is shown in Figure 8b. To achieve these standards, the CO_2 emission should be adjusted to approximately 163 Mt CO_2 and the Jet A fuel to approximately 52 Mt, which is the estimated demand for Jet A fuel in 2050. At 6.7%, a reduction of approximately 93% is required. As in the previous IATA, the reduction ratio for each year was shown for a gradual reduction, but the absolute amount of reduction was larger than before, so IATA's 2040 target had to be achieved in 2020. This goal appears to be very difficult to achieve, as more than 85% of the aircraft currently in operation must be converted immediately. By 2050, the conversion of all narrow and wide-body aircraft to aircraft using eco-friendly fuel, such as LH_2, is necessary. Approximately 10% of regional jets also require conversion, so early conversion is emphasized to reach the final goal by 2050.

5.3. Annual LH_2 Fuel Requirement at 100% Conversion (Up to 2050)

Next, we estimated the amount of LH_2 supply required for the above targets. In this estimation, a comparison was performed by considering the additional fuel required when converting from the existing Jet A fuel to the LH_2 fuel for each aircraft classification. When fuel is changed from jet fuel to LH_2, fuel consumption may increase by 9~14% depending on the type of aircraft [26]. Accordingly, in Figure 9, the case of the change in the LH_2 fuel from the simple jet fuel and the case of applying the conversion coefficient according to the previous aircraft type are separately expressed as weighted (expressed as (w) in the figure). Compared to the conversion from simple Jet A fuel to LH_2 fuel, it was found that the amount of fuel increased by approximately 10% when the fuel added for each aircraft was considered.

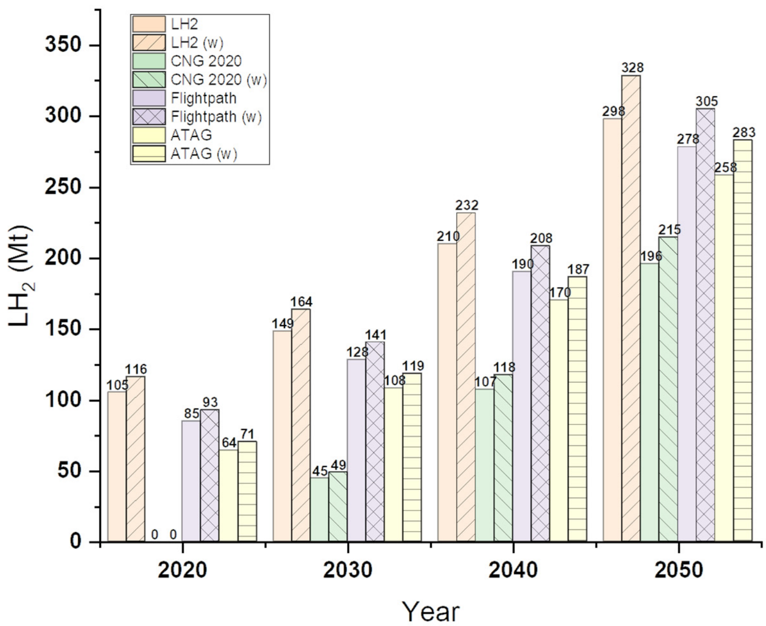

Figure 9. Total estimated LH_2 fuel demand.

As of 2020, it was predicted that 105 to 116 Mt LH_2 would be required for 100% LH_2 fuel aircraft, 61% of 100% conversion in IATA, and 80% of LH_2 fuel in Flightpath 2050. Following Flightpath 2050, the share increases over the years, with 86% of the total in 2030, 90% in 2040, and 92% in 2050, resulting in a difference of only 8% compared to 100% conversion.

5.4. Jet Fuel and LH_2 Price Sensitivity Analysis

Next, sensitivity analysis for each year was conducted according to jet fuel and LH_2 fuel price changes. Based on Figure 5b, the expected prices of jet fuel and LH_2 fuel from 2020 to 2050 were estimated and are shown in Figure 10. In Figure 10, the case of the change in the LH_2 fuel from the simple jet fuel and the case of applying the conversion coefficient according to the aircraft type is separately expressed as weighted (expressed as (w) in the figure). When checking each result, the price difference occurred 4.7 to 5.2 times in 2020 due to the high production cost of LH_2. However, for 2030, the gap gradually began to decrease due to the decrease in LH_2 production cost by 1.7~1.87 times, and for 2040, it was predicted that the total cost of jet fuel would be higher than that of LH_2 fuel. LH_2 currently has a high production cost due to the similar small-scale action plant and green or blue H_2 production plant, but if the demand increases, the production cost is expected to decrease by more than 60% due to the installation of a large-scale plant, which can be maintained for almost 2030 years. Therefore, if the gradual conversion from jet fuel to LH_2 fuel is carried out, it will be possible to prevent a rapid cost increase due to the high production cost in the early stages.

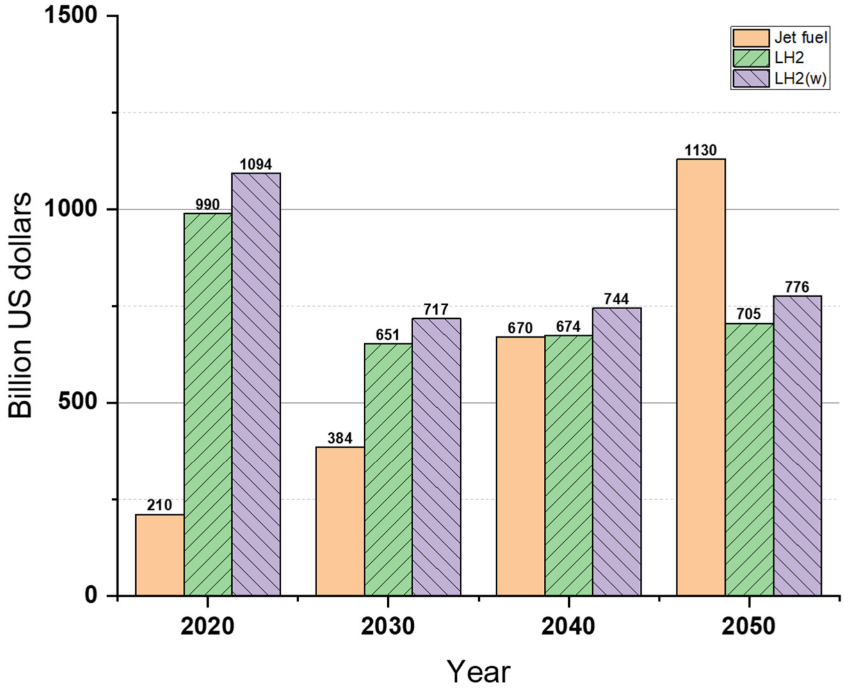

Figure 10. Total estimated annual fuel cost trend.

6. Conclusions

This study proposes a method to estimate the amount of hydrogen in the aviation field to fuel, and through this, the LH_2 fuel estimation model is proposed. In addition, a case study was conducted to determine how much LH_2 fuel was required when various environmental regulations were satisfied.

Through the three-step conversion process, the entire LH_2 fuel estimation model was proposed. The flight of an aircraft is composed of the LTO cycle and the CCD cycle. In the LTO cycle, fuel consumption can be calculated based on the standard time required by ICAO. Next, in the CCD cycle, the fuel consumption according to the flight distance can be calculated, and an aircraft fuel model was produced based on the EMEP/EEA method. Second, the amount of Jet A and equivalent LH_2 fuel were estimated based on the total energy consumed, and a fuel model of the LH_2 aircraft was produced by reflecting the change in engine efficiency over time. Finally, by using the LH_2 fuel model manufactured for each aircraft, the entire LH_2 fuel model was proposed by applying conversion factors according to the change in aircraft market share and categories (narrow body/wide body/regional jet).

The analysis of the aircraft's transition from Jet A to LH_2 to meet the regulations of CNG 2020 and IATA/Flightpath 2050 showed that by 2030, a reduction in the use of 114 Mt Jet A is required, with a reduction of approximately 66% in the use of 1612 Mt CO_2 and 512 Mt Jet A by 2050. The criteria for IATA/Flightpath 2050 required a more significant amount of CO_2 emissions and Jet A fuel to be reduced when targeting the reduction rather than maintenance of carbon emissions in CNG 2020. Looking at this as a gradual transition for each year, the results were approximately 60% in 2020, 70% in 2030, 80% in 2040, and 94–95% in 2050.

Currently, the amount of hydrogen produced worldwide is estimated to be approximately 70 Mt according to the IEA, which can achieve only 60% of the 116 Mt needed in the aviation sector in 2020. In addition, many fields require hydrogen in addition to the aviation field due to hydrogen vehicles that achieve eco-friendly standards. With the transition of this energy paradigm, the demand for hydrogen energy is expected to be approximately 10 times higher than in 2015. As the demand for the hydrogen economy increased worldwide, the U.S. and Korea prepared a hydrogen economy roadmap. A strategy was established to meet the rapidly growing demand for hydrogen through the transition from the current production structure to a large-scale production system. Considering the increase in hydrogen energy demand and the decrease in hydrogen production costs, it is expected that the amount of hydrogen fuel required by the aviation field can be sufficiently satisfied.

As a result of comparing the cost part of the existing Jet A fuel and the cost part of LH_2, in the case of Jet A fuel, the unit price provided tends to increase continuously. On the other hand, in the case of LH_2, it is composed of the basic H_2 production cost and the similar action cost, and it is expected that if the current small-scale plant is converted to a large-scale plant, it will decrease by up to 50% or more compared to the current LH_2 supply unit. Comparing this with the annual requirement for each fuel, the demand for Jet A fuel and LH_2 fuel continues to increase by 1.69 to 1.83 times in terms of cost due to the unit price per barrel increase. On the other hand, in 2020, the price difference of LH_2 was 4.7~5.2 times that of Jet A fuel, but after 2030, the cost of LH_2 will be lower than that of Jet A fuel, and thereafter, the LH_2 cost will be maintained at a similar level. Therefore, if the gradual transition from Jet A fuel to LH_2 fuel is carried out, it will be possible to prevent a rapid increase in costs due to the high production cost in the early stages.

Due to COVID-19, the aviation share price has decreased, and the conversion rate is expected to be delayed by more than a few years, depending on the recovery rate of the share price. However, there will be no change in the overall tone in the big framework for CO_2 emission reduction based on the Paris Agreement, so the need to convert existing fossil fuel-based Jet A fuel into alternative fuels is ongoing. Accordingly, efforts to achieve "zero carbon" or "true zero" through 100% conversion into eco-friendly fuel will continue, and accordingly, investment/conversion in the demand for hydrogen fuel and infrastructure construction will be essential, so pre-construction and prediction will be necessary. Therefore, the conversion rate and fuel estimation model of existing aircraft to eco-friendly aircraft presented in this study are expected to be available as predictive models for using hydrogen, an eco-friendly fuel, in aircraft.

Through this study, a fuel model for LH_2-fueled aircraft and a total required fuel model for the aviation sector was proposed. In addition, through several case studies, the conversion rate from Jet A to LH_2 fuel of the aircraft to satisfy environmental regulations and the corresponding cost were compared. It can be used as a basis for building infrastructure by examining the impact of hydrogen as a fuel for future aircraft and estimating capacity.

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Nomenclature

List of symbols	
m_{fuel}	Mass of aviation total fuel
m_{LTO}	Mass of LTO (landing and take-off) cycle fuel
m_{CCD}	Mass of CCD (climb, cruise and descent) cycle fuel
$m_{additional}$	Mass of additional fuel
$m_{i,JetA}$	Mass of Jet A fuel by aircraft type
m_{i,LH_2}	Mass of liquid hydrogen fuel by aircraft type
$m_{total,JetA}$	Mass of total Jet A fuel
m_{total,LH_2}	Mass of total liquid hydrogen fuel
m_{JetA}	Mass of Jet A fuel
m_{LH_2}	Mass of liquid hydrogen fuel
E_{JetA}	Jet A fuel-specific energy density
E_{LH_2}	Liquid-hydrogen-specific energy density
η_{JetA}	Jet A fuel energy efficiency
η_{LH_2}	Liquid hydrogen energy efficiency
ϕ_i	Aircraft share of aircraft classification and type
C_{JetA}	The total price of Jet A fuel
C_{LH2}	The total price of liquid hydrogen fuel
c_{JetA}	The unit price of Jet A fuel
c_{LH2}	The unit price of liquid hydrogen fuel
$a_{k,i}$	Coefficient of Jet A fuel estimation model, $k = 1, \cdots, 6$
$a'_{k,i}$	Coefficient of liquid hydrogen fuel estimation model, $k = 1, \cdots, 6$
List of abbreviations	
CO_2	Carbon dioxide
H_2	Hydrogen
LH_2	Liquid Hydrogen
ICAO	International Civil Aviation Organization
CNG 2020	Carbon Neutral Growth from 2020
IATA	International Air Transport Association
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
NOx	Nitrogen Oxide
LNG	Liquefied Natural Gas
SOx	Sulfur Oxide
ATAG	Air Transport Action Group
ACARE	The Advisory Council for Aeronautical Research in Europe
SAFs	Sustainable Aviation Fuels

LCAFs	Lower Carbon Aviation Fuels
DLR	the Federal Republic of Germany's research centre for aeronautics and space
PAX	Passenger
LTO	Landing and Take-Off
CCD	Climb, Cruise and Descent
ICCT	International Council on Clean Transportation
IEA	International Energy Agency

References

1. International Civil Aviation Organization (ICAO). On Board a Sustainable Future: 2016 Environmental Report. 2016. Available online: http://www.icao.int/environmental-protection/Documents/ICAO%20Environmental%20Report%202016.pdf (accessed on 22 August 2022).
2. International Energy Agency (IEA). Energy Technology Perspectives 2016 Model Results. 2016. Available online: http://www.iea.org/etp/etp2016/secure/ (accessed on 22 August 2022).
3. Airbus, 2016. Global Market Forecast 2016–2035. Available online: http://www.airbus.com/company/market/global-market-forecast-2016--2035/ (accessed on 22 August 2022).
4. Boeing, 2016. Current Market Outlook 2016. Available online: http://www.boeing.com/commercial/market/long-term-market/downloads/ (accessed on 22 August 2022).
5. The Paris Agreement. 2015. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 22 August 2022).
6. International Civil Aviation Organization (ICAO). Resolutions Adopted at the 38th Session of the Assembly, Provisional Edition. 2013. Available online: http://www.icao.int/Meetings/a38/Documents/Resolutions/a38_res_prov_en.pdf (accessed on 22 August 2022).
7. International Air Transport Association (IATA). Climate Change. 2017. Available online: http://www.iata.org/policy/environment/pages/climate-change.aspx (accessed on 22 August 2022).
8. International Civil Aviation Organization (ICAO). Consolidated Statement of Continuing ICAO Policies and Practices Related to Environmental Protection—Global Market-Based Measure (MBM) Scheme. 2016. Available online: http://www.icao.int/environmentalprotection/Documents/Resolution_A39_3.pdf (accessed on 22 August 2022).
9. European Union, Flightpath 2050, Europe's Vision for Aviation, 2011. Available online: https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf (accessed on 22 August 2022).
10. Zhang, C.; Hui, X.; Lin, Y.; Sung, C. Recent development in studies of alternative jet fuel combustion: Progress, challenges, and opportunities. *Renew. Sustain. Energy Rev.* **2016**, *54*, 120–138. [CrossRef]
11. Graham, W.R.; Hall, C.A.; Morales, M.V. The potential of future aircraft technology for noise and pollutant emissions reduction. *Transp. Pol.* **2014**, *34*, 36–51. [CrossRef]
12. Cansino, J.M.; Román, R. Energy efficiency improvements in air traffic: The case of Airbus A320 in Spain. *Energ. Pol.* **2017**, *101*, 109–122. [CrossRef]
13. Schäfer, A.W.; Evans, A.D.; Reynolds, T.G.; Dray, L. Costs of mitigating CO_2 emissions from passenger aircraft. *Nat. Clim. Change* **2016**, *6*, 412–418. [CrossRef]
14. Linke, F.; Grewe, V.; Gollnick, V. The implications of intermediate stop operations on aviation emissions and climate. *Met. Zeitsch.* **2017**, *26*, 697–709. [CrossRef]
15. Yılmaz, İ.; İlbaş, M.; Taştan, M.; Tarhan, C. Investigation of hydrogen usage in aviation industry. *Energy Convers. Manag.* **2012**, *63*, 63–69. [CrossRef]
16. Contreras, A.; Yiğit, S.; Özay, K.; Veziroğlu, T.N. Hydrogen as aviation fuel: A comparison with hydrocarbon fuels. *Int. J. Hydrog. Energy* **1997**, *22*, 1053–1060. [CrossRef]
17. Janic, M. The potential of liquid hydrogen for the future 'carbon-neutral' air transport system. *Transp. Res. Part D Transp. Environ.* **2008**, *13*, 428–435. [CrossRef]
18. Kousoulidou, M.; Lonza, L. Biofuels in aviation: Fuel demand and CO_2 emissions evolution in Europe toward 2030. *Transp. Res. Part D Transp. Environ.* **2016**, *46*, 166–181. [CrossRef]
19. Janic, M. Is liquid hydrogen a solution for mitigating air pollution by airports? *Int. J. Hydrog. Energy* **2010**, *35*, 2190–2202. [CrossRef]
20. Cecere, D.; Giacomazzi, E.; Ingenito, A. A review on hydrogen industrial aerospace applications. *Int. J. Hydrog. Energy* **2014**, *39*, 10731–10747. [CrossRef]
21. Airbus, ZEROe. Available online: https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe (accessed on 22 August 2022).
22. Westenberger, A. *Liquid Hydrogen Fueled Aircraft-System Analysis*; Final Technical Report (Publishable Version), Cryoplane Project; European Commission: Brussels, Belgium, 2003.
23. Brewer, G.D. *Hydrogen Aircraft Technology*; CRC Press: Boca Raton, FL, USA, 1991.
24. Seymour, K.; Held, M.; Georges, G.; Boulouchos, K. Fuel Estimation in Air Transportation: Modeling global fuel consumption for commercial aviation. *Transp. Res. Part D Transp. Environ.* **2020**, *88*, 102528. [CrossRef]

25. European Commission, Report of the Group Personalities European Aeronautics: A Vision for 2020 Meetings Society's Needs and Winning Global Leadership. 2001. Available online: http://www.aerohabitat.eu/uploads/media/01-02-2005_-_European_Aeronautics__a_vision_for_2020__500KB_.pdf (accessed on 22 August 2022).
26. International Air Transport Association (IATA), Aircraft Technology Roadmap to 2050, 2019. Available online: https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/Technology-roadmap-2050.pdf (accessed on 22 August 2022).
27. Müller, C.; Kieckhäfer, K.; Spengler, T.S. The influence of emission thresholds and retrofit options on airline fleet planning: An optimization approach. *Energy Policy* **2018**, *112*, 242–257. [CrossRef]
28. Berger, R. Hydrogen: A Future Fuel for Aviation? 2020. Available online: https://www.rolandberger.com/publications/publication_pdf/roland_berger_hydrogen_the_future_fuel_for_aviation.pdf (accessed on 22 August 2022).
29. Baharozu, E.; Soykan, G.; Ozerdem, M.B. Future aircraft concept in terms of energy efficiency and environmental factors. *Energy* **2017**, *140*, 1368–1377. [CrossRef]
30. Abbe, G.; Smith, H. Technological development trends in Solar-powered Aircraft Systems. *Renew. Sustain. Energy Rev.* **2016**, *60*, 770–783. [CrossRef]
31. Edelman, S.; Poza, D.P.I.; Krieg, T. Fuel cell APU's in commercial aircraft—An assessment of SOFC and PEMFC concepts. In Proceedings of the 24th International Congress of the Aeronautical Sciences, Yokohama, Japan, 29 August–3 September 2004; pp. 1–10.
32. Green Car Congress. Available online: https://www.greencarcongress.com/2008/05/dlr-and-airbus.html (accessed on 22 August 2022).
33. German Aerospace Center (DLR). Available online: https://www.dlr.de/content/en/articles/aeronautics/research-fleet-infrastructure/dlr-research-aircraft/antares-dlr-h2-out-of-operation.html (accessed on 22 August 2022).
34. Aerospace Technology. Available online: https://www.aerospace-technology.com/projects/hy4-aircraft/ (accessed on 22 August 2022).
35. European Union. Hydrogen-Powered Aviation. 2020. Available online: https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf (accessed on 22 August 2022).
36. The Commonwealth Scientific and Industrial Research Organisation (CSIRO). Opportunities for Hydrogen in Commercial Aviation. 2021. Available online: https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-commercial-aviation (accessed on 22 August 2022).
37. Airbus, Tomorrow's Airports: Future Energy Ecosystems? Available online: https://www.airbus.com/en/newsroom/news/2021-06-tomorrows-airports-future-energy-ecosystems-0 (accessed on 22 August 2022).
38. OliverWyman, GLOBAL FLEET & MRO MARKET FORECAST. Available online: https://www.oliverwyman.com/content/dam/oliver-wyman/v2/publications/2022/feb/MRO-2022-Master-file_v5.pdf (accessed on 22 August 2022).
39. CIRIUM, World Airliner Census 2020. Available online: https://www.flightglobal.com/download?ac=73559 (accessed on 22 August 2022).
40. European Environment Agency (EEA). *EMEP/EEA Emission Inventory Guidebook e 2013*; EEA Technical Report No 12/2013; European Environment Agency: Copenhagen, Denmark, 2013; ISSN 1725-2237.
41. National Academies of Sciences, Engineering, and Medicine. *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*; The National Academies Press: Washington, DC, USA, 2016. [CrossRef]
42. Epstein, A.H. Aeropropulsion for Commercial Aviation in the Twenty-First Century and Research Directions Needed. *AIAA J.* **2014**, *52*, 901–911. [CrossRef]
43. Graver, B.; Rutherford, D.; Zheng, S. The ICCT Report, CO2 Emissions from Commercial Aviation: 2013, 2018, AND 2019. Available online: https://theicct.org/wp-content/uploads/2021/06/CO2-commercial-aviation-oct2020.pdf (accessed on 22 August 2022).
44. Air Transport Action Group (ATAG). Fact Sheet. 2019. Available online: https://aviationbenefits.org/media/166838/fact-sheet_4_aviation-2050-and-paris-agreement.pdf (accessed on 22 August 2022).
45. U.S. Energy Information Administration, Kerosene-Type Jet Fuel Prices: U.S. Gulf Coast [WJFUELUSGULF], Retrieved from FRED, Federal Reserve Bank of St. Louis. Available online: https://fred.stlouisfed.org/series/WJFUELUSGULF (accessed on 22 August 2022).
46. International Renewable Energy Agency (IRENA). *Global Renewables Outlook: Energy transformation 2050*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2020.
47. Al Ghafri, S.; Munro, S.; Cardella, U.; Funke, T.; Notardonato, W.; Trusler, J.P.M.; Leachman, J.; Span, R.; Kamiya, S.; Pearce, G.; et al. Hydrogen Liquefaction: A Review of the Fundamental Physics, Engineering Practice and Future Opportunities. *Energy Environ. Sci.* **2022**, *15*, 2690–2731. [CrossRef]
48. Connelly, E.; Penev, M.; Elgowainy, A.; Hunter, C. Current Status of Hydrogen Liquefaction Costs; DOE Hydrogen and Fuel Cells Program Record; U.S. Department of Energy. 2019. Available online: https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf (accessed on 22 August 2022).