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Article

Investigating Hydrogen as a Potential Alternative to Kerosene in Fueling Commercial Aircraft

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SUMMARY

Growing climate concerns have intensified research into zero-emission transportation fuels, notably hydrogen. Hydrogen is considered a clean fuel because its only major by-product is water. This project analyzes how hydrogen compares to kerosene as a commercial aircraft fuel with respect to cost, CO_2 emissions, and flight range. We hypothesized that hydrogen planes would emit less CO_2 but would have higher fueling costs and shorter ranges than current kerosene planes. The fuel cost and emissions per km cruise of hypothetical hydrogen combustion and fuel cell planes using grey (methane-derived), blue (methane-derived with partial carbon capture), and green (electrolysis-derived using renewable electricity) hydrogen were calculated and compared to those of a kerosene Boeing 737-400 (737). These metrics were determined through chemical and physical analyses based on publicly available data. The blue hydrogen combustion plane is a promising short-term option because with 4-34% carbon capture, it had lower cost and emissions than the 737 while requiring minimal modifications to current infrastructure. The green hydrogen fuel cell plane is a promising long-term option because it had no CO_2 emissions and would become cost competitive once the net electrolysis and fuel cell efficiency increases from the current 40% estimate to 48%. However, both hydrogen planes had relatively shorter ranges than the 737 due to the low volumetric density of hydrogen. Through this work, we have shown that hydrogen holds potential as an economically viable clean alternative aircraft fuel, but the development of high-density solid-state hydrogen storage materials is crucial for the success of hydrogen aviation.

INTRODUCTION

Today, three fossil fuels—coal, natural gas, and oil—provide for approximately 80% of the U.S.'s energy demands and account for over 80% of global energy consumption (1,2). However, burning fossil fuels for energy has taken an extreme toll on the environment. In addition to causing heat and water pollution, the combustion of fossil fuels releases carbon dioxide (CO_2), a greenhouse gas, into the atmosphere, increasing global temperatures and contributing to climate change (3). As the devastating effects of climate change—such as more extreme weather and rising sea levels—are becoming increasingly apparent over time, countries around the world have placed a great emphasis on discovering alternative energy sources to fulfill the ever-increasing global appetite for energy (4,5). It is crucial to the survival of future generations that we quickly transition away from fossil fuels and towards clean energy sources.

One of the significant contributors to global emissions is aviation, which was responsible for 2.4% of the United States' 2018 carbon emissions from the combustion of kerosene, a component of jet fuel (6). Like the gasoline that powers cars, kerosene is a fossil fuel that consists of various liquid hydrocarbons and is obtained through refining petroleum (7). To meet the transportation needs of a growing global economy and population, aviation must overcome its reliance on kerosene to become environmentally sustainable.

Substantiated by advancements in hydrogen-powered automobiles, hydrogen has become a promising potential fuel source to power aircraft over recent years (8). Hydrogen has a specific energy density of 120 MJ/kg, which is almost three times that of kerosene and over 100 times that of lithium-ion batteries (9). Hydrogen can either be combusted directly in the presence of oxygen to drive combustion engines, or it can be reacted with oxygen in a fuel cell to produce an electric current that powers electric engines. The main by-product from both processes is water vapor, meaning that there are no direct CO_2 emissions from the use of hydrogen to generate energy (10).

Though the use of hydrogen does not emit CO_2, various methods of producing hydrogen do. Currently, nearly all commercially produced hydrogen in the U.S. is produced via steam-methane reforming (SMR). Commercial hydrogen factories and petroleum refineries react high-temperature steam (700˚C to 1000˚C) with methane in the presence of a catalyst to produce hydrogen and carbon monoxide (CO) (11). Because CO is a deadly gas, it is reacted with additional steam to produce CO_2 and even more hydrogen. Hydrogen produced purely through SMR is classified as grey hydrogen. Although this is the least expensive method, SMR emits considerable amounts of CO_2 (11). However, the large amount of emissions from SMR can be reduced through carbon capture and storage (CCS) technology, which recovers CO_2 at the source using various chemical methods and stores them deep underground. Current CCS technologies can capture up to 80% of released CO_2 (12). When SMR is combined with CCS, the produced hydrogen is classified as blue hydrogen (the only difference between grey and blue hydrogen is the inclusion of CCS). Hydrogen can also be produced via the electrolysis of water, a process that splits water into hydrogen and oxygen using an electric current. This method is appealing because it has the potential to generate hydrogen with zero or near-zero CO_2 emissions, depending on the source of electricity (13). The cost, efficiency, and emissions of various sources of electricity must be considered; for example, clean energy sources such as wind, solar, and nuclear would result in near zero CO_2 emissions (13). Hydrogen produced through electrolysis using renewable electricity is classified as green hydrogen.

Our study analyzes the use of hydrogen as an alternative to kerosene in fueling commercial aircraft by comparing CO_2 emissions, fuel costs, and range. We hypothesized that hydrogen planes would have lower emissions than kerosene planes but cost more to fuel and have shorter ranges. From the metrics determined through chemical and physical calculations in this study, we concluded that hydrogen is an economically viable alternative fuel for commercial aircraft

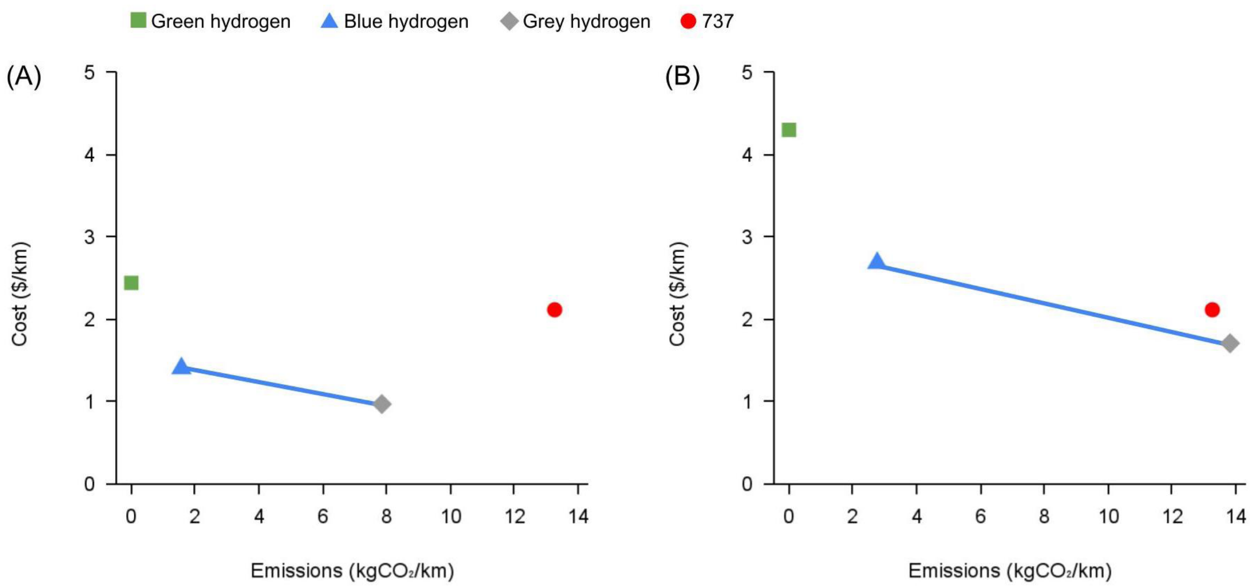

Figure 1: Fuel cost and emissions of various plane-fuel combinations. (A) Fuel cost and emissions of hydrogen combustion planes using the three types of hydrogen compared to those of the 737. (B) Fuel cost and emissions of hydrogen fuel cell planes using the three types of hydrogen compared to those of the 737. The blue hydrogen plane values are graphed as a line because the % of carbon captured during SMR can be varied. The left endpoints represent 80% CCS (blue hydrogen), the right endpoints represent 0% CCS (grey hydrogen), and the line represents everything in between 0% and 80% CCS (also blue hydrogen).

	Cost ($/km)	Emissions ($kgCO_2$/km)	Range (km)
Kerosene (737)	2.12	13.27	4261
Combustion plane			
Grey	1.71	13.83	2055
Blue	1.71 - 2.69	13.83 - 2.77	2055
Green	4.30	0	2055
Fuel cell plane			
Grey	0.971	7.85	3617
Blue	0.971 - 1.41	7.85 - 1.57	3617
Green	2.44	0	3617

Table 1: Calculated fuel cost, emissions, and ranges of all seven plane-fuel combinations. The blue hydrogen plane metrics are ranges because the percent of carbon captured during SMR can be varied.

with low- to zero-CO_2 emissions. The ranges of hydrogen planes would surpass those of current planes as hydrogen storage density increases with the development of new materials-based technologies. The transition to carbon-neutral hydrogen aviation would greatly reduce global emissions and the effects of climate change.

RESULTS

Through the use of scientific modeling, we made chemical and physical calculations based on publicly available data to analyze the efficiency of hypothetical hydrogen planes in comparison to a current Boeing 737-400 (737) (14-19). Efficiency was analyzed with respect to cost of fuel/km cruise, CO_2 emissions/km cruise, and maximum range through the usage of three types of data: market energy prices, chemical compound data, and aircraft technical specifications.

In this study, we analyzed two independent variables: the type of hydrogen plane (combustion vs. fuel cell) and the type of hydrogen fuel (blue vs. grey vs. green). Between these different plane-fuel combinations, we held constant the plane's required thrust and flight speed—which were the same as those of the 737. All of the hydrogen planes were assumed to use 40 m³ cryogenic hydrogen storage tanks. Our strategy for calculating the dependent variables was to determine the fuel mileages of each plane as well as the cost and emissions per kg of each fuel. We then used these values to calculate cost/km, emissions/km, and range of each plane-fuel pair.

Looking at fuel cost, the green hydrogen planes both had higher costs than the 737 **(Figure 1, Table 1)**. The blue/grey hydrogen fuel cell and blue hydrogen combustion planes had both lower costs and emissions than the 737, and all hydrogen planes had shorter ranges than the 737 **(Table 1).** Most hydrogen planes had lower CO_2 emissions than the 737, but the cost increased as the emissions decreased **(Figure 1)**. Additionally, the full cell planes had both lower costs and emissions than the combustion planes.

We then performed a more detailed cost-benefit analysis between the blue hydrogen combustion plane and the 737. We determined that as the percent CCS for blue hydrogen combustion planes increased, CO_2 emissions decreased and cost increased linearly **(Figure 2)**. At above 4% CCS, the blue hydrogen combustion plane had lower CO_2 emissions than the 737; at below 34% CCS, it had a lower cost than the 737 **(Figure 2)**.

Next, we performed an analysis to determine the projected breakeven point between the green hydrogen fuel cell plane and the 737 as the net electrolysis and fuel cell efficiency increases in the future. As the net electrolysis and fuel cell efficiency of green hydrogen planes increased, the cost decreased inversely, breaking even with the 737 cost at 48% efficiency **(Figure 3).**

We also considered the range of the planes as a function of hydrogen storage density. Using the current assumption of liquid hydrogen storage, the fuel cell plane had a slightly shorter range than the 737 while the combustion plane had half the range of the 737 **(Figure 4)**. As the hydrogen storage density increased, the maximum range of the hydrogen planes increased proportionally, breaking even with the 737 range at 84 kg/m³ and 148 kg/m³ (fuel cell and combustion, respectively) **(Figure 4)**.

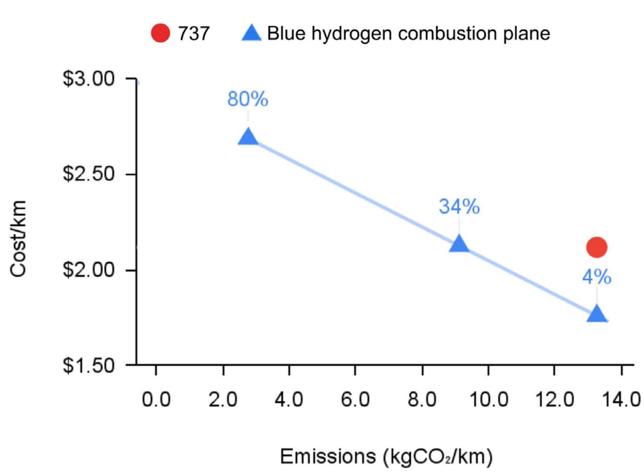

Figure 2: Fuel cost and emissions of a blue hydrogen combustion plane compared to those of the 737. The blue line represents cost/emission values of a blue hydrogen combustion plane with various % CCS; notable points on this line have the % CCS labelled. The cost breakeven between the planes is at 34% CCS, while the emissions breakeven is at 4% CCS.

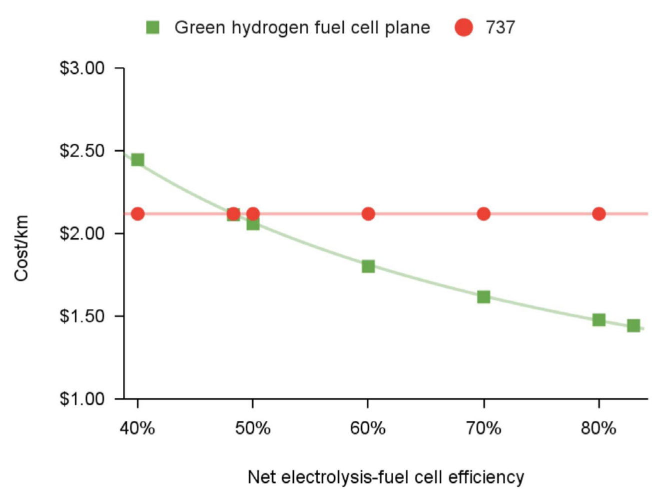

Figure 3: Fuel cost of a green hydrogen fuel cell plane as a function of the net electrolysis-fuel cell efficiency, compared to that of the 737. The current efficiency is 40%, and the maximum theoretical efficiency is 83%. The cost breakeven between the planes is at 48% efficiency.

DISCUSSION

From our study, the most viable near-future option for hydrogen planes is the blue hydrogen combustion plane. With 4% to 34% CCS, the blue hydrogen combustion plane had both lower costs and emissions compared to the 737 **(Figure 2)** (9). The blue/grey hydrogen fuel cell plane also had lower costs and lower CO_2 emissions than the 737, and the blue hydrogen combustion plane could be engineered with fewer modifications to current planes than fuel cell planes. In addition to being cheaper, blue hydrogen is more favorable than green hydrogen because it relies on natural gas and already-developed SMR infrastructure, making the transition to hydrogen fuel smoother (12). In addition, the U.S. tax code section 45Q provides a tax credit of $20 per ton of CO_2 captured and stored, which would offset the cost of blue hydrogen (20). Thus, the blue hydrogen combustion plane is the most practical near-future option.

Looking at long-term solutions, the green hydrogen fuel cell plane is the best option as it released zero CO_2 emissions and was more efficient than a green hydrogen combustion plane **(Figure 1)**. The green hydrogen fuel cell plane would become cost-competitive once the net electrolysis and fuel cell efficiency increases from 40% to 48% **(Figure 3)**. In addition, numerous other factors can increase the economic viability of the green hydrogen fuel cell plane. First, renewable electricity prices are decreasing due to innovations in wind and solar power (21). This decrease in price will lead to the cost of green hydrogen to decrease as well. Another factor in play is that 25 countries around the world have carbon taxes (of which the U.S. is not one). Canada, for example, has a carbon tax of $32USD/tonne$CO_2$ that increases by $8USD/tonne$CO_2$ per year (22). With a carbon tax of $25/tonne$CO_2$, the green hydrogen fuel cell plane would be cheaper to fuel than the 737 at the current 40% net efficiency.

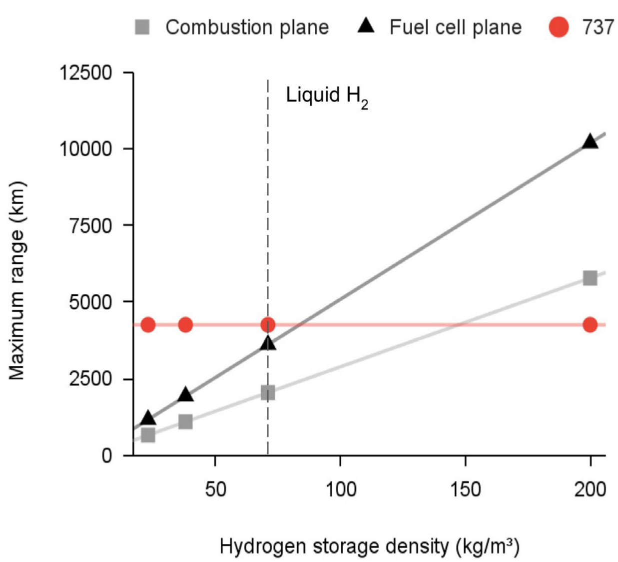

Figure 4: The maximum ranges of a hydrogen combustion plane and a hydrogen fuel cell plane as a function of hydrogen storage density, compared to that of the 737. The dotted line represents the hydrogen storage density of liquid hydrogen; the points on this line represent the ranges of the planes using liquid hydrogen.

Efficient hydrogen storage is the main barrier to be overcome for hydrogen planes to become practical. While hydrogen has a relatively high gravimetric energy density, it has a relatively low volumetric energy density. Using liquid hydrogen fuel, both hydrogen planes had shorter ranges than the 737 due to liquid hydrogen's relatively low volumetric density of 71 kg/m³ **(Figure 4)** (9). In addition, since the liquid hydrogen must be stored at -253˚C in a bulky insulating tank, it would no longer be stored in the wings (where kerosene is stored) (9). If the cryogenic tank is integrated inside the fuselage, it would take up around a quarter of passenger/cargo space, resulting in lost revenue. High density solid-state hydrogen storage materials are a promising solution to the problem of hydrogen storage due to the relationship between hydrogen storage density and range: when hydrogen storage density increases, the range of the hydrogen plane increases linearly **(Figure 4)**. For example, research is being conducted into using ammonia borane (NH_3BH_3) as a potential high density hydrogen storage material with a density of over 150 kgH/m³ (23). NH_3BH_3 can be hydrolyzed to release gaseous hydrogen as needed. A fuel cell plane storing hydrogen as ammonia borane would have a range twice that of one storing liquid hydrogen. Research is also being conducted into Kubas Manganese Hydride-1 (KMH-1), which is a chemical hydride with a hydrogen adsorption density of 197 kgH/m³, almost three times that of liquid hydrogen (24). With the successful implementation of KMH-1, the range of a fuel cell plane would be over 10,000 km—enough to fly from San Francisco to London. The development of solid-state hydrogen storage materials would also solve the problem of a large cryogenic tank, as solid-state hydrogen is much lower maintenance and may be able to be stored in the wings, freeing up fuselage space. In addition, solid-state hydrogen is generally safer as there is a lower risk of gas leaking and causing explosions (24). For the aforementioned reasons, the development of high-density solid-state hydrogen storage materials is crucial for the success of hydrogen-powered aviation.

In this study, multiple expenses such as operating expenses, initial capital investments, government subsidies, and market fluctuations were not included in the final calculations in order to simplify calculations and focus on fewer variables. Although this study showed hydrogen could be viable as a fuel to replace kerosene, it will be important to continue this research in order to identify potential financial gains or losses when developing hydrogen fuel technology and determine where money will need to be allocated to offset the cost of developing hydrogen planes. Further research would analyze the effects of the aforementioned expenses as well as other inconsistencies between kerosene planes and hydrogen planes, such as the possible losses in revenue due to decreased cabin space from a cryogenic tank.

This study only considered CO_2 emissions (which are

Kerosene		
Price (16)	0.554	\$/kg
Density (18)	810	kg/m^3
Emissions	3.13	$kgCO_2/kg$
Refinery % of product used as fuel*	10	%
Life-cycle emissions	3.47	$kgCO_2/kg$
Specific energy (LHV)	44.03	MJ/kg
Boeing 737-400		
Cruise speed (20)	850.4	km/hr
Tank capacity (20)	20.1	m^3
Engine SFC (20)	18.89	g/(kN*s)
Cruise thrust (20)	47.8	kN (total)
Fuel burn rate	0.902	kg/s
Power consumption	39.73	MW
Power output	11.3	MW
Engine efficiency	28.4	%
Fuel mileage	0.262	km/kg
Cost	2.12	\$/km
Emissions	13.3	kg CO_2/km
Range	4261	km

Table 2: Calculated values for kerosene and the 737. The range calculated was only 1.5% higher than Boeing's quoted 737 range, showing that the fuel mileage calculated was reasonably accurate.
* Assumed values

Hydrogen		
HHV (17)	286	kJ/mol
LHV (17)	121.7	MJ/kg
MW (17)	2.016	g/mol
Liquefaction energy (26)	0.65	\$/kgLH$_2$
Electrolysis		
Efficiency*	80%	
Energy output	39.4	kWh/kg
Energy input	49.25	kWh/kg
Renewable electricity price (21)	0.05	\$/kWh
Green cost	2.46	\$/kgH$_2$
SMR		
Efficiency*	70	%
Energy output	286	kJ/mol H_2
Energy input	408.6	kJ/mol H_2
Methane HHV (17)	892	kJ/mol
Methane price (19)	0.00258	\$/mol CH_4
Methane input	0.458	mol/mol H_2
Grey cost	0.0012	\$/mol H_2
Grey emissions	10.00	$kgCO_2/kgH_2$
CCS cost (25)	0.088	\$/kgCO$_2$

Table 3: Calculations for cost and emissions of SMR and electrolysis. The blue hydrogen metrics are calculated as a function of the percent of carbon captured and the CCS cost.
* Assumed values

the majority of emissions) and not other trace emissions such as nitrogen oxides (NO_x), which cause acid rain, smog, and ozone depletion (15). Hydrogen combustion emits 90% less NO_x emissions than kerosene, making hydrogen planes even more appealing in terms of minimizing pollution (15). While this study considered the CO_2 emissions from the fuel production, it did not account for the life-cycle emissions of the manufacturing of the plane parts or fuel transportation. Future studies could account for indirect emissions from hydrogen planes as well as their various other trace emissions.

Decarbonizing the aviation industry is a pressing challenge. Our study suggests that hydrogen is an economically viable alternative fuel for commercial aircraft with low- to zero-emissions. In order to speed up the commercialization of hydrogen planes, further research should be conducted into high density solid-state hydrogen storage materials, cheaper and more efficient fuel cell catalysts, liquid hydrogen tank integration on commercial aircraft, and alternative methods of CCS. Overcoming numerous engineering and economic challenges will also need to be addressed through coalitions including manufacturers, researchers, policymakers, and the general public. Although there are multiple obstacles that need to be addressed before the commercialization of hydrogen planes, hydrogen planes could pave the way towards an eventual carbon-neutral hydrogen economy, benefiting Earth and all its future inhabitants.

MATERIALS AND METHODS

Calculations of Specific Energy, Emissions, and Cost of Kerosene

To determine the specific energy and emissions of kerosene, a computational combustion analysis was performed on a surrogate of kerosene—74% n-decane,

	Hydrogen combustion plane		Hydrogen Fuel Cell plane	
Tank capacity*	40	m^3	40	m^3
Engine efficiency*	28.4	%	50	%
Power output	11.3	MW	11.3	MW
Power consumption	39.7	MW	22.57	MW
Fuel burn rate	0.327	kg/s	0.185	kg/s
Cruise speed	850.4	km/hr	850.4	km/hr
Fuel mileage	0.723	km/kg	1.274	km/kg
Range	2055	km	3617	km

Table 4: Calculations for the mileages of a hydrogen combustion plane and a hydrogen fuel cell plane. The fuel mileage is independent of the type of hydrogen fuel used. It was assumed that both hydrogen planes would store hydrogen in a 40 m^3 cryogenic tank.
* Assumed values

15% propylbenzene, and 11% propylcyclohexane (by mol) (16). In this analysis, the weighted averages (by mol) of the emissions/mol, combustion enthalpy, and molar masses of each component of the surrogate were used to determine the emissions/kg and specific energy of kerosene through dimensional analysis **(Table 2)** (17). Ethylene was then analyzed with the same process as an even cruder surrogate of kerosene to verify the specific energy and emissions determined from the former surrogate (17). The current market price ($/gal) and density of kerosene (kg/m^3) were used to determine the cost per kg of kerosene through dimensional analysis (14). To simplify calculations, we assumed that a petroleum refinery uses 10% of its product as fuel and estimated the lifecycle emissions/kg of kerosene using the combustion analysis data.

Calculations of Cost, Emissions, and Range of the 737

The CFM56-3C1 (737's engines) specific fuel consumption and cruise thrust was used to calculate the fuel burn rate of the 737 through dimensional analysis (18). The fuel mileage was then calculated by dividing the cruise speed by the fuel burn rate. The 737 power consumption was then calculated by dividing the fuel burn rate by kerosene's specific energy. Multiplying the cruise thrust by the cruise speed, the required power output was determined. Dividing power output by power consumption, the 737 engine efficiency was calculated. Finally, the cost/km and emissions/km were found by dividing each of the fuel cost and emissions by the fuel mileage. The range was determined by multiplying the tank volume by the fuel mileage **(Table 2)**.

Calculation of Costs and Emissions of Hydrogen Fuels

To calculate the emissions and cost of the hydrogen fuels, efficiency analyses were performed on SMR and electrolysis **(Table 3)**. Dividing the higher heating value (HHV) of hydrogen by the process efficiencies of SMR and electrolysis gives the required input energies in terms of how much hydrogen is produced. The market prices of renewable electricity and methane were then used to determine the cost of the input energy and thus the cost/kg of green hydrogen and grey hydrogen, respectively (19). For grey hydrogen, the SMR reaction was used to calculate the CO_2 emissions from SMR and the CO_2 emissions from methane combustion were used to determine the total emissions/kg of grey hydrogen. The CO_2 emissions of blue hydrogen were determined as a function of the percent of carbon captured: the emissions were the remaining fraction of emissions from SMR after CCS. The cost of blue hydrogen was also a function of the percent of carbon captured: the cost was the cost of capturing the CO_2 added to the grey hydrogen cost (25). The liquefaction cost was added to the final costs of all three hydrogen fuels (26).

Calculation of Cost, Emissions, and Range of Hydrogen Planes

To calculate the fuel mileages of the two hydrogen planes, dividing the required power output (determined previously in the 737 calculations) by the combustion engine/fuel cell efficiencies gives the respective required power inputs. For simplicity, we assumed that a hydrogen combustion engine would have the same efficiency as a kerosene combustion engine. Dividing the required power consumption by hydrogen's specific energy (LHV: 121.7 MJ/kg) results in each plane's fuel burn rate (17). The fuel burn rate was used along with the cruise speed to determine the fuel mileage of each plane **(Table 4)**. For each plane-fuel combination, the fuel emissions/kg and cost/kg were divided by the plane mileage to determine the final emissions/km and cost/km metrics, respectively **(Table 1)**. The range was calculated by multiplying the fuel mileage by the tank volume **(Table 4)**.

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