Hydrogen Fuel Cell Technology: An Overview

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IN

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Submitted by

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This thesis/dissertation/project report entitled "**HYDROGEN FUEL CELL TECHNOLOGIES IN AVIATION: AN OVERVIEW**" by **ARBAB NAFEES (18SCME1010049)** is approved for the degree of Bachelor of Technology in mechanical engineering.

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3. Project Supervisor was referred to for preparing the report.
4. Specifications regarding the thesis format have been closely followed.
5. The contents of the thesis have been organized based on the guidelines.
6. The report has been prepared without resorting to plagiarism.
7. All sources used have been cited appropriately.
8. The report has not been submitted elsewhere for a degree.

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ABSTRACT

According to the International Air Transport Association (ATA), the industry has improved its record of fuel efficiency: fuel burned per passenger per kilometer has dropped by half since 1990. This case study aims to find a powerful and efficient propulsion system that runs on renewable resources. We’ll dive deep into the study of fuel cells, particularly solid oxide fuel cells for their fuel to energy conversion ratio and close to no emissions. This study will help us understand what fuel cell design, where it’ll be installed, materials of the cathode, and anode. Different materials for electrolytes will be compared to analyze each of their impact on a flight’s performance which can drastically reduce the price per ticket and make air travel much more economical and environmentally clean. What storage method will be preferred for space efficiency, more capacity to reduce travel time by fueling just once, and to keep hydrogen safe from igniting itself. Fuel cells are still a work in progress due to their lack of instant power, so engineers combined them with a gas turbine creating a hybrid setup that achieves an amazing efficiency. Airlines such as Airbus, Eviation, and Zunun Aero are working on All-Electric Aircraft (AEA) where their planes are powered by hydrogen fuel cells.

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List of abbreviations

1. IATA – International Air Transport Association
2. FC - Fuel Cell
3. AEA - All-Electric Aircraft
4. LH_2 – Liquid Hydrogen
5. SNG – Substituting Natural Gas
6. FCV – Fuel Cell Vehicle
7. SOFC – Solid Oxide Fuel Cell
8. YSZ – Yttria Stabilized Zirconia
9. GCO – Dopped Gadolinium Ceria
10. LSGM – Lanthanum Gallate
11. ScSZ – Scandium Stabilized Zirconia
12. CGH_2 – Compress Gaseous Hydrogen
13. CPV – Cryogenic pressure vessel
14. ATM – Air Traffic Management

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CHAPTER 1

INTRODUCTION

The rapid growth in aviation traffic in recent decades and the expectation of continued development have raised the demand of aircraft manufacturers to enhance the economy and reduce the environmental effect. As a result, future aircraft will have to meet higher environmental criteria as well as increased economic and productivity demands. Manufacturers are facing problems like manufacturing hydrogen on a large scale. Recent Studies highlight the issues like to safe storing of hydrogen in Commercial vehicles, locations, storage facilities, etc. Another major issue researchers are facing transportation of that manufactured hydrogen to its destination. These airplanes are heavy and need a very combustible fuel known as jet fuel (a blend of kerosene and, crude oil). Fuel Cells are the best method to utilize the potential of hydrogen as a clean emission-free as an alternative to fossil fuels. The components of a fuel cell are quite expensive, but the long-lasting and low maintenance features compensate for it. They have found that fuel cell systems can replace present propulsion systems, hydrogen fuel cells can generate up to 300% more power from 1kg of liquid hydrogen (LH2) compared to 1kg of jet fuel. The fundamental reason to use liquid hydrogen to power airplanes is the high specific (energy/mass) heat of combustion, which is 2.8 times that of conventional fuels like kerosene. If the liquid hydrogen tank and insulation mass are a small percentage of hydrogen, the mass advantage of liquid hydrogen fuel results. Fuel cells are preferred over standard Lithium-ion batteries because of their low emissions, higher efficiency, higher power density, lightweight, and less space. The main benefits of using fuel cell-powered (FCs) are that their very efficient and emit no harmful gases/emissions. The only by-product is water and heat. This literature survey helps us to conclude that solid oxide fuel cells are the best because of their operating conditions, electrolyte material, and environmentally friendly energy generation. Unmanned aircraft systems (UAS) that are powered by electricity are now used for a range of surveillance missions. Based on its high efficiency, cheap cost, and great dependability, electric propulsion is frequently favoured over the usage of tiny internal-combustion engines (ICE). However, the energy density of commercial batteries limits the battery-powered unmanned aircraft systems, which has prompted the development of better FC-based systems. The demonstration of an FC-system supplying supplemental power for an Airbus 320's hydraulic and electric systems and the Boeing fuel-cell demonstrator jet was demonstrated in Spain and France in February 2008 respectively. The first issue is improving energy density, which is less of an issue in other industries but critical in the aerospace industry. NASA designed FC systems for the Apollo and Gemini space missions in partnership with Pratt & Whitney and General Electric. Long-range aircraft powered by kerosene and hydrogen are thus contrasted at present and future technological levels. The choice of huge long-range aircraft was made because their large fuel capacities indicate the upper limit of prospective performance gains from hydrogen adoption. The structural mass of the airplane, on the other hand, is likely to alter dramatically in the next decades because of the increased use of composite materials in the load-bearing structures. The fact that a quantity of liquid hydrogen with the same energy content as kerosene has approximately four times the storage volume has a significant impact sign. Liquid hydrogen cannot be stored in the same way as kerosene can and must be kept in specific tanks. To prevent liquid hydrogen from entering the gaseous phase, these tanks must have more resistance to high pressures than normal kerosene tanks and have excellent thermal insulation. Liquid hydrogen is kept as a saturated liquid/gas combination at low temperatures. The interior insulation system keeps liquid hydrogen at a near-room temperature and prevents heat conduction by preventing direct contact between it and the tank construction (i) The tank pressure must be greater than atmospheric pressure to avoid air ingestion, which might result in an explosion. (ii) fuel tanks must be designed for long periods due to maintenance issues. Metal hydrides are also be used to store gaseous hydrogen, for a venting pressure of 2 bars against 1 bar the tank volume must be raised by 5%. An ellipsoid promises highly adaptable geometric designs that include ellipsoidal heads and elliptical shells. For the needed internal pressures, which are twice as higher as regular cryogenic systems in terms of magnitude, the tank-wall thickness increases dramatically. The cryogenic tank requires some energy to convert the hydrogen phase and warm it to ambient temperatures. The enthalpy of vaporization for LH_2 is 20K is 450kJ/kg and specific heat is 13.68kJ/kg/K.

MATERIALS	WEIGHT (kg)	AMOUNT OF ENERGY CONSUMED (MJ/kg)	TOTAL (GJ)
Aluminium	14.9	219.5	3.4
Polyester	6.9	169	1.275
Net			4.59

Table 1: Energy consumption for a tank’s production

One of the most important characteristics of a propulsion system is energy production in a particular amount of fuel (Whkg^{-1}). Researchers have proposed an experimental setup that consists of a fuel cell and gas turbine to work in such a way that the fuel cell (will deliver instant power) while take-offs and the gas turbines operate to keep the plane moving while the fuel cell supports the gas turbine whenever there is a power lag from the gas turbine. To safely store hydrogen, we use cryogenic tanks that maintain a chilling temperature of -273°F (169.4°C) to keep hydrogen in a liquid state, it saves a lot of space and allows you to store more liquid hydrogen for longer flights.

Time	USA	CHINA	SPAIN	JAPAN	OTHER COUNTRIES
2005-2009	Fuel Cell – 12	Steam reformation – 14	Ethanol steam reforming – 6	Steam Reformation - 13	Steam reformation – 70
2009-2013	Fuel Cell - 13	Biohydrogen production – 17	Decomposing methane - 13	Water splitting - 11	Steam reformation - 84
2013-2017	Photocatalysis - 15	Photocatalysis - 113	Steam reformation- 11	Steam reforming - 9	Photocatalysis - 329

Table 2: Research on hydrogen production on done every 4 years

As seen in table 1 steam reforming was a popular method to produce electricity and even to produce hydrogen which is not a clean method to produce hydrogen. Steam reforming has been around for the past 40 years and has been a valuable commercial fuel, the primary gas produced during the process depends on the operating temperatures, pressures, steam, and carbon feed rates. Two extreme conditions in steam reforming are (i) reducing gas production which involves primary steam reforming at high temperatures (982°C or higher) (ii) substituting natural gas (SNG) production that requires steam reforming at the highest pressure possible.

Photocatalyst consists of two words a photon and a catalyst (which alters the speed of a chemical reaction). Photocatalysts are substances that accelerate/decelerate the rate of a chemical reaction on exposure to light. This phenomenon is called photocatalysis. Photocatalysis includes the reactions that take place by utilizing a semiconductor and primarily light.

CHAPTER 2

HYDROGEN

Hydrogen is a fundamental element that can be found in every part of the universe as a gas. It may be made using a variety of processes, including methane gas, reforming, coal gasification, and water electrolysis. Green hydrogen is the best sort of created hydrogen since it is made by electrolyzing two water molecules and one hydrogen molecule. With a few changes, hydrogen gas may be utilized in normal gasoline-powered internal combustion engines, although it emits nitrogen. PEM is the most extensively explored fuel cell, and it was finally used in FCVs. We can produce hydrogen that is emissions-free if we use renewable energy sources properly. The current focus is on hydrogen as a low-emission alternative fuel, with the possibility of hydrogen becoming the dominant fuel in the future.

2.1.COMPARISON OF HYDROGEN TO OTHER FUELS

NO.	Types of Fuel	The energy produced per unit mass (J/Kg)	The energy produced per unit volume (J/m^3)	Carbon emission specific (kg/kg fuel)	Energy reserve factor
1.	Hydrogen gas	143	0.014	0	.99
2.	Liquid hydrogen	143	10.11	0	.99
3.	Fuel oil	44	38.6	.85	.78
4.	Gasoline	46	38.65	.84	.75
5.	Jet fuel	45.50	34.85	-	.74
6.	Liquefied petroleum gas	48	35.30	-	.62
7.	Liquefied natural gas	50	24.40	-	.61
8.	Methanol	22	23	.50	.23
9.	Ethanol	29	18.10	.50	.37
10.	Biodiesel	37	23.60	0.51	-
11.	Natural gas	51	33	0.47	.75

12.	Coal	31	-	0.50	-

2.2. PROPERTIES OF HYDROGEN

Hydrogen is a colorless, odorless, tasteless, and nonpoisonous gas under normal conditions on Earth. It typically exists as a diatomic molecule, meaning each molecule has two atoms of hydrogen; therefore, pure hydrogen is commonly expressed as H_2. The present focus is on hydrogen as a low-emission alternate fuel, the probability of hydrogen becoming the next all-rounder fuel is very high due to its power output, efficiency, and applications. It will be the principal energy source that will be supplied to houses, manufacturing plants, vehicles, etc.

- Hydrogen is highly flammable; it only takes a small amount of energy to ignite it and make it burn. It also has a wide flammability range, meaning it can burn when it makes up 4 to 74 percent of the air by volume.
- Hydrogen can be produced from renewable resources, such as by reforming ethanol (this process emits some carbon dioxide) and by the electrolysis of water (electrolysis is very expensive).
- The combustion of hydrogen does not produce carbon dioxide (CO_2), particulate, or sulfur emissions. It can produce nitrous oxide (NO_X) emissions under some conditions.

2.2.1. CHEMICAL PROPERTIES OF HYDROGEN

NO.	PROPERTIES	VALUES	UNITS
1.	Molecular weight	2.015.5	Amu
2.	Density (Gaseous)	0.0837.5	kg/m^3
3.	High heating values	141.90	MJ/kg
4.	Low heating values	119.90	MJ/kg
5.	Temperature (boiling)	20.4	K
6.	Density (liquid)	7	Kg/m^3
7.	Critical point pressure	1283	kN/m^2
8.	Critical point temperature	32.95	K
9.	Critical point density	30	kg/m^3
10.	Temperature (self-ignition)	859	K
11.	Temperature (flame)	2318	K

2.3. HYDROGEN ECONOMY

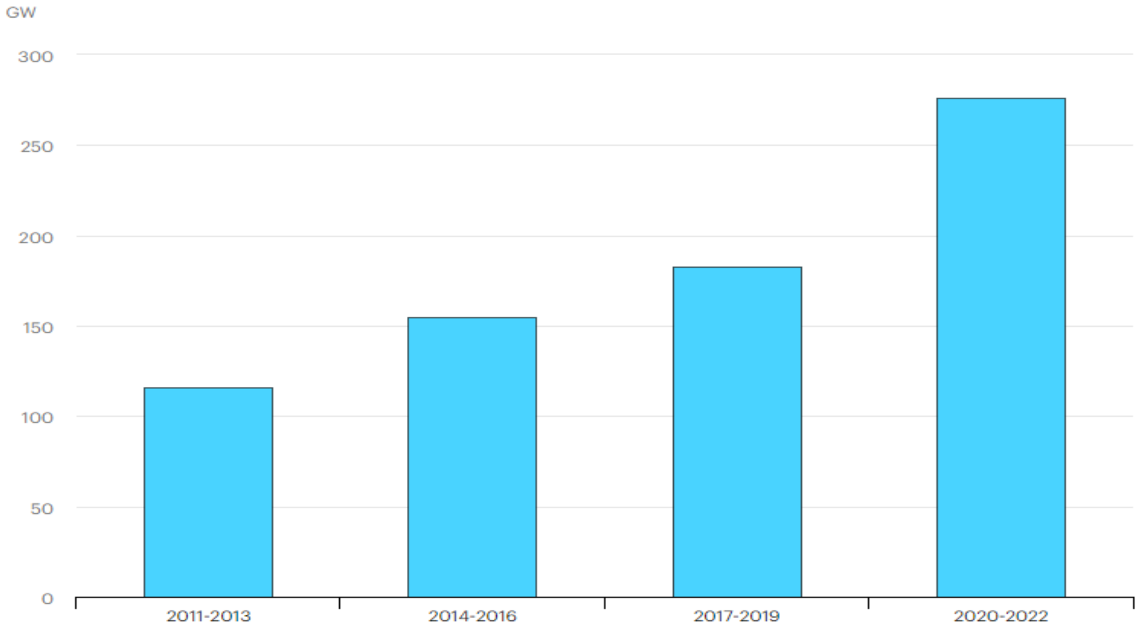
Hydrogen and fuel cells will fulfill global energy demands by 2050, according to an exhaustive and optimistic study. We'll need to establish small hydrogen production stations to deliver big amounts of hydrogen to everyone. Hydrogen produced by natural gas steam reforming is currently substantially less expensive than hydrogen produced by electrolysis. Hydrogen production is currently the cheapest centralized gas reformer and the most expensive in electrolyzer systems. In a process known as electrolysis, an electrolyzer uses an electric current to separate water into oxygen and water. Electrolyzers are expected to have strong learning effects, and power prices from diverse renewables might be extremely inexpensive if hydrogen synthesis takes place when there is plenty of it. Natural gas's low cost is one of the main reasons for its current extensive use in hydrogen generation. In comparison to traditional gasoline-powered automobiles and alternatives such as rechargeable electric vehicles, fuel cell vehicles and hydrogen mobility remain prohibitively costly. The country's financial situation and the government's readiness to work on laws to reduce fossil fuel usage will determine the future of renewable hydrogen generation. Because hydrogen is created using sustainable resources such as solar energy, geothermal energy, or biomass, the hydrogen economy thrives. Japan is one of the most technologically sophisticated countries in the world, and it is driving Asia's renewable hydrogen economy forward. In the near term, hydrogen is produced by electrolysis.

2.3.1. CARBON ECONOMY

It refers to the green ecological economy based on low energy consumption and low pollution. The current social production activities mean that the level of CO_2 emissions in the electric power industry in China is the world’s largest and thermal power plant consumes about 70% of China’s annual output of raw coal.

The following initiatives that can be taken are: -

- More investments must be bought into renewable technologies
- Applying different methods to reduce the carbon footprint
- Cooperation of developed countries will help greener technology to grow in that country.



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Growth of renewable energy resources from 2011 to 2022

CHAPTER 3

ALTERNATE FUELS

Alternative fuels also known as non-conventional/advanced fuels are used as fuels rather than Petroleum, Diesel, Coal, etc. Renewable sources of energy are the next step to a cleaner future where everything is powered by Hydrogen, solar and hydro. Alternative fuels are a very important development due to the growing population and growing number of vehicles which contributes to a lot of damage to the environment through emissions of CO, NOx, CO2, etc, several automotive companies like Hyundai and Toyota are manufacturing hydrogen fuel cell-powered vehicles and are currently available on the global market for sale.

1. Hydrogen is the most promising alternative fuel because of its abundance in the universe, hydrogen is currently being used in fuel cell vehicles. It is extracted from water, coal, and natural gas.
2. Biodiesel is a renewable biodegradable manufactured fuel from various vegetable oils, animal fats/ leftovers. Biodiesel is used exactly like diesel in compression-ignition engines.

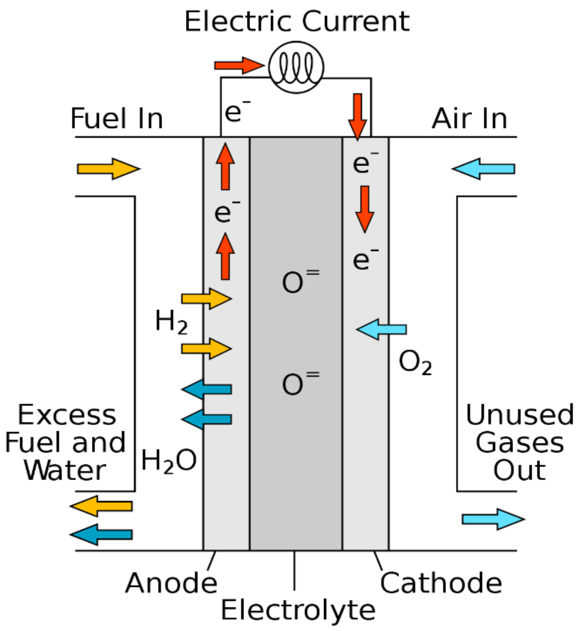
3. Ethanol is made from corn and plant materials, most of the petroleum in the market has some percentage of ethanol. Some parts of the world have an ethanol blend of 50-80%
4. Methane is also a major component of natural gas. Because methane can be captured in landfills, it can be burned to generate electricity, heat buildings, or power garbage trucks. Capturing methane before it enters the atmosphere also helps mitigate the effects of climate change.
5. Geothermal energy is generated by the earth’s core and the best locations are large water reservoirs available in Alaska and Hawaii. Earth’s heat energy can be extracted from anywhere with heat pumps.
6. Solar energy is derived from the sun where the solar panels absorb all the heat and generate electricity. This alternate fuel is one of the best because sunlight is abundant.

To extract energy from sunlight there is a need to install solar panels which is very expensive, and the amount of electricity generated depends on the intensity of the sunlight where you live.

CHAPTER 4

FUEL CELL

A fuel cell produces electricity using the chemical energy of hydrogen or other fuels cleanly and efficiently. Only electricity, water, and heat are produced when hydrogen is used as a fuel. Fuel cells are unusual in that they can use a wide range of fuels and feedstocks, and they can power systems as large as a utility power plant and as tiny as a laptop computer. Fuel cells function similarly to batteries, except they do not need to be recharged. If fuel is available, they create power and heat. Fuel cells provide several advantages over traditional combustion-based technologies, which are now employed in many power plants and cars. Fuel cells have better efficiency than combustion engines, converting the chemical energy in the fuel straight to electrical energy with efficiencies of up to 60%. When compared to combustion engines, fuel cells emit less or no pollutants. Hydrogen fuel cells release only water and no carbon dioxide, addressing important climate issues. There are also no air contaminants at the place of operation that cause pollution and health issues. Because there are few moving elements in fuel cells, they operate quietly.



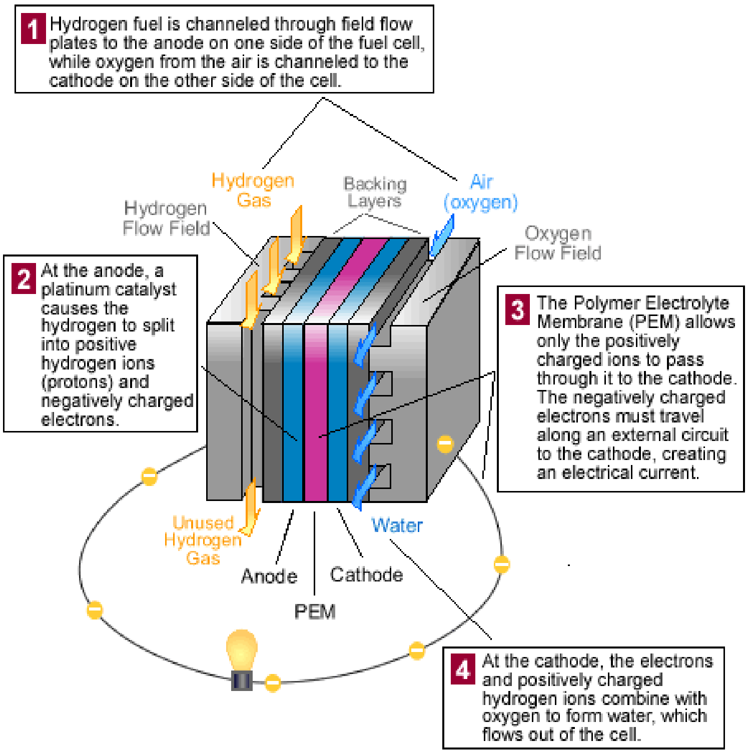
Fuel Cell	Efficiency	Applications	Advantages	Disadvantages
AFC	50-60%	Used for back power for homes Used as a power source in vehicles	This fuel cell uses materials that are efficient and stable. It is cheaper and operates at low	Sensitive to Carbon dioxide in air and fuel Management of electrolyte (aqueous),

			temperatures. It has a faster boot time.	electrolyte conductivity
MCFC	40-50%	Can be used for electricity-based facilities	Fuel flexibility and efficient, suitable for power cycles.	Higher corrosion and temperature and prone to breakdown of components, higher start up time and has lower power density
PAFC	30-40%	Used in grid networks	Has high tolerances for foreign particles in fuel	Expensive catalysts, long start up time, Sulfur sensitivity
PEMFC	50-55% H_2	Used for backup power, used in automobiles, used in electricity grid networks, also used in portable power banks	Corrosion can be avoided by using a solid electrolyte. Can be used in cold temperature and has quick start up.	The catalysts are expensive, sensitive to impurities
SOFC	55-60%	Used in auxiliary power units as a secondary source, and used as power for a lot of electric facilities	Fuel flexibility and has high efficiency, it has potential reversible operation. Solid electrolyte And is suitable for all power cycles	The cell components have high temperature, corrosion resistance. Short number of shutdowns and longer time for start-up

Types of Fuel Cells

4.1. PRINCIPLE

A device that works on the principle of generating electrical energy by converting chemical energy is known as a Fuel cell. A fuel cell is categorized on the type of electrolyte they’re based on. The three important main components of the fuel cell are the anode, cathode, and a specific type of electrolyte where the electrolyte is sandwiched between the anode and the cathode. A fuel cell is made up of two electrodes sandwiched around an electrolyte: a negative electrode (or anode) and a positive electrode (or cathode). The anode receives fuel, like hydrogen, while the cathode receives air. A catalyst at the anode of a hydrogen fuel cell divides hydrogen molecules into protons and electrons, which go along distinct pathways to the cathode. The electrons go through an external circuit, causing electricity to flow. Protons go through the electrolyte to the cathode, where they combine with oxygen and electrons to form water and heat.



1 Hydrogen fuel is channeled through field flow plates to the anode on one side of the fuel cell, while oxygen from the air is channeled to the cathode on the other side of the cell.

2 At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.

3 The Polymer Electrolyte Membrane (PEM) allows only the positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along an external circuit to the cathode, creating an electrical current.

4 At the cathode, the electrons and positively charged hydrogen ions combine with oxygen to form water, which flows out of the cell.

4.2. PERFORMANCE

A polymer electrolyte in the shape of a thin, permeable sheet is used in proton exchange membrane (PEM) fuel cells. The working temperature is at 80 degrees C, and the efficiency is around 40 to 50 percent. The fuel cell efficiency is a function of the power density at which the fuel cell is running, not a single value. At maximum power production, the efficiency is usually the lowest. The fuel cell's optimal nominal efficiency, which results in the least expensive power produced, is determined not only by its performance characteristics but also by its economics, which includes the fuel cell's capital cost and the cost of hydrogen. The output of a cell typically ranges from 50 to 250 kW. These cells run at a low enough temperature to be appropriate for houses and vehicles, and the solid, flexible electrolyte will not leak or split. However, their fuels must be refined, which necessitates the employment of a platinum catalyst on both sides of the membrane, adding expenses. As electrolytes, solid oxide fuel cells (SOFC) employ a hard, ceramic composition of metal oxides (chemically, O2) (such as calcium or zirconium). The efficiency is around 60%, and the working temperature is over 1,000 degrees Celsius. Several authors have suggested solid oxide fuel cells for their large electricity grid applications. Solid oxide fuel cells can also run-on biogas, which is extracted from biowaste, solid oxide fuel cells are very versatile in terms of fuel intake such as methane, biogas, natural gas, and hydrogen. The output of the cells can reach

100 kW. A reformer is not necessary to extract hydrogen from the fuel at such high temperatures, and waste heat may be recovered to generate further energy. In both my papers we mainly talk about the potential of a fuel cell, the future of fuel cells depends on their performance and cost price. The initial production cost of fuel cells is too high for commercial purposes, but the performance and efficiency of a fuel cell keep us going on its research and development. Proton exchange membrane fuel cell is preferred for its low operating temperatures, but it uses an expensive catalyst like platinum and requires very refined fuel. In order to maintain the quality and lifetime of pemfc we've to obtain high-quality hydrogen that too from renewable resources.

Properties	Yttria stabilized Zirconia (YSZ)	Dopped Gadolinium Ceria (GCO)	Lanthanum gallate (LSGM)	Scandium-Stabilized Zirconia (ScSZ)
1. Compatibility	excellent stability in oxidizing Reduces environmental damage	Great compatibility with cathode material	Great compatibility with cathode materials	Great stability in oxidizing and reducing environmental damage.
2. Stability	Great Mechanical stability	At low pO_2, a mixed electronic-ionic conductor is formed		better long-term stability than Yttria stabilized zirconia (YSZ)
3. Practical applications	Most of the solid oxide fuel cells use YSZ electrolyte		Ga-evaporation at a low partial pressure of oxygen	Availability and price of scandium
4. Conductivity	Low ionic conductivity (especially YSZ)	Electronic conduction at $PO_2 \rightarrow$ low Open circuit voltage	Incompatible with NiO	
5. Temperature	800°C - 1000°C	600°C - 800°C	1000°C - 1200°C	450°C - 550°C

Types of electrolytes

CHAPTER 5

STORAGE

The modern world's economy is based on free energy that has been stored for millions of years in nature. Hydrogen is a clean, renewable fuel that is also good for the environment. With current technology, storing and transferring hydrogen on a big scale is a substantial challenge. The heating value of hydrogen per unit mass is the highest. Because hydrogen has a low energy density, storing it in precise locations/circumstances is difficult. A high-pressure gas cylinder with a maximum pressure of 20 MPa is the most used storage mechanism. Good H2 storage materials are cost-effective, light, have excellent adsorption and desorption kinetics, and are recyclable.

5.1. STORAGE METHODS

1. Pressurized storage tanks (350-700 bar) are hydrogen stored in high-impact resistant tanks that give enough protection from a collision and have a huge capacity but are too tough to accommodate in a compact vehicle. These tanks have to be commercially available in small to large sizes, the larger the tank the more expensive it is.

2. Liquid hydrogen (LH_2) storage system is high in density and relatively inexpensive, we face evaporative losses just after 3 days of idle usage. Austenite material stainless steel is used to manufacture cryogenic tanks because of its quality to insulate gases at low temperatures. The inner lining of the high pressurized vessel is made of carbon fiber and is covered with reflective materials for thermal insulation. This storage tank cools the hydrogen down to 20K, turning it into liquid hydrogen because of the immense temperature and high pressure. This method lets the manufacturers store more hydrogen. Cryogenic storage technology is widely used in the transportation industry and large-scale hydrogen facilities.

3. Artificially dug caverns are used to store hydrogen and are very good in keeping hydrogen from escaping or reacting with air because the walls of the caverns are covered with inert rock salt. These caverns are 400 to 800 ft below the ground, these kinds of caverns are being used in Canada, U.S.A, Germany, and the U.K.

5.2. Challenges

The technical difficulty for hydrogen storage is storing enough hydrogen for a conventional driving range (>300 miles) while staying within the vehicle's weight, volume, efficiency, safety, and cost limits. These systems' durability over their entire performance lifetime must also be evaluated and certified, as must acceptably refilling times.

- The weight and volume of hydrogen storage are too high compared to conventional fuel storage, that’ll directly impact the range of the vehicles. Lightweight, durable storage tanks need to be designed for long-distance travel.

- The cost of present hydrogen storage tanks is high when compared to traditional gasoline, and diesel tanks. Cost-efficient components need to be used, and high volume and large manufacturing plants should be able to reduce the cost per commercial tank.

- The energy required to get hydrogen in and out of the tank is an issue, compressed and cryogenic storage tanks are promising but the energy required to liquefy and pressurize hydrogen is proving to be difficult.

5.3. Types of hydrogen storage in different states

	Category	**Type**
1.	Chemical storage (metal hydride)	Magnesium hydride (MgH_2), Sodium hydride (NaH), calcium hydride (CaH_2)
2.	Physical storage (metal-organic framework)	PCN-6 PCN, porous coordination network
3.	Gas Storage	Compressed H_2
4.	Liquid hydrogen	Liquid hydrogen (LH_2)

CHAPTER 6

TRANSPORTATION

New infrastructure must be installed to transport the hydrogen from the place it’s being produced to different fuelling stations, industries, and residential areas to power homes. Hydrogen is sent to liquefaction plants to liquefy hydrogen before transporting through pipelines (existing pipelines for gasoline), cryogenic tankers, etc.

On-site hydrogen production is a good way to produce cheap hydrogen and avoid transportation costs, on-site hydrogen production can be done behind fuelling stations, and airport terminals. Produced hydrogen can be stored on-site and used when needed.

Hydrogen is transported in super-insulated cryogenic tanker trucks for long distances, after liquefaction of hydrogen it is distributed to required places where the hydrogen is vaporized back to its gaseous form. Cryogenic tankers are preferred over traditional transportation methods because they can store more hydrogen than normal due to hydrogen being liquified and consuming less space.

6.1. Challenges

Cost reduction, energy efficiency, hydrogen purity, and hydrogen leakage are all important concerns in hydrogen transport. More research is needed to assess the trade-offs between hydrogen production and distribution alternatives when viewed as a whole system.

The development of a national hydrogen delivery system is also a major development. It will take time and integrate all this technology into the hydrogen delivery ecosystem. The demands and resources for delivery infrastructure will vary by geography and market type, such as rural, urban, and industrial purposes. As the demand for hydrogen increases and delivery technologies improve, infrastructure options will improve.

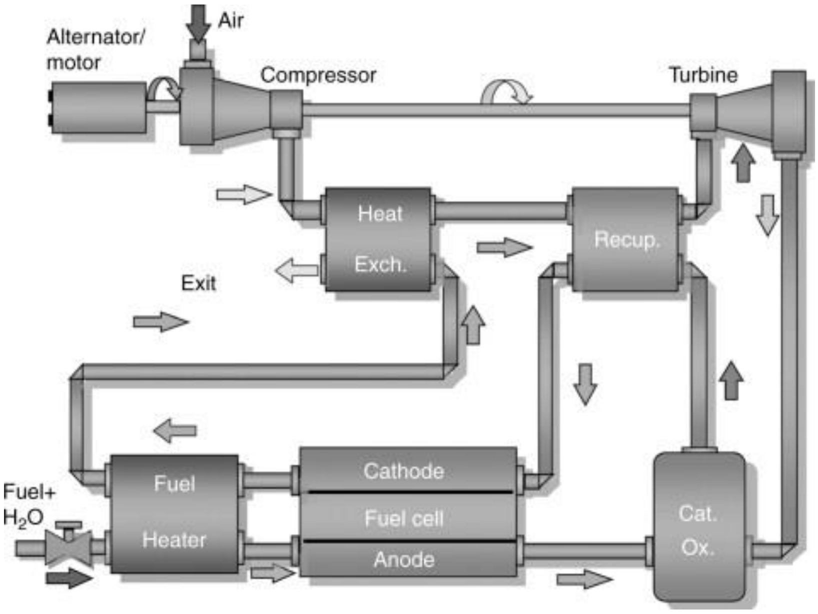
CHAPTER 7

FUEL CELL GAS TURBINE HYBRID TECHNOLOGY

The gas turbine is a rotary engine that uses a flow of combustion gases to extract energy (which produces 10Whkg^{-1}). Ambient air is taken into the engine intake, where it is boosted in pressure and temperature. The combination of gas turbine technology and high-temperature fuel cells creates a fuel-flexible power generating platform with ultra-high efficiency and ultra-low emissions. The combination of fuel cell and gas turbine systems allows for the utilization of synergies such as the conversion of waste heat into extra energy and compression power, fuel cell pressurization, and air pre-heating.

- Instead of employing an indirect heating approach, direct integration of the FC removes the requirement for extra high-temperature heat exchangers.
- The performance of the fuel cell is improved when it is pressurized.
- Pre-heating is provided by air compression, which increases the heat available to drive the turbine and generate more energy.

The SOFC-GT topping cycle is used in a variety of applications, from small, distributed generation units to huge 100-MW generator units. In both systems, the FC characteristics are comparable, with the pressurized SOFC delivering up to 25% more power than that produced under atmospheric pressure working conditions. Due to the greater operating voltage and lower air pre-heating required, the principal advantage of a SOFC topping cycle is fuel cell pressurization. With a steady power supply and a pressure of 10 atm, the voltage rises by 20%, increasing efficiency and lowering the current.



7.1. LIQUID HYDROGEN (LH_2) IN AVIATION

Liquid hydrogen meets the requirements and can remove all combustion pollutants. Another advantage of hydrogen is that it may be used as a liquid fuel substitute or in a fuel cell to generate electricity. Short-range aircraft may benefit from electrical fuel cells, whereas long-range and higher-payload aircraft may benefit from hydrogen combustion. Hydrogen fuel cells are currently commonplace in vehicles such as automobiles, buses, and planes. The volumetric density of liquid hydrogen fuel is lower than that of kerosene. Even though the airplane requires less fuel to finish a flight, the space that this fuel would occupy is projected to be roughly 4 times bigger than that of kerosene.

Areas of Effect	Advantages of Liquid hydrogen	Disadvantages of Liquid hydrogen
Combustion	Higher specific energy (119190kJ/kg), higher efficiency, higher combustion temperature	Four times lower energy/unit volume
Aircraft Design	Reduced gross weight by 26%, Weight reduced from wings by 18%. Smaller engines and reduced noise, Cruise’s lift/drag ratio	With the more voluminous fuselage, you’ve to install a cryogenic fuel system

	reduced by 15%	
Airport infrastructure	Airports will have hydrogen production facilities on-site for faster refueling time for planes and other support vehicles	The amount of hydrogen stored for refueling
Emissions	No emissions of carbon monoxide, carbon dioxide	

Liquid Hydrogen in aviation

CHAPTER 8

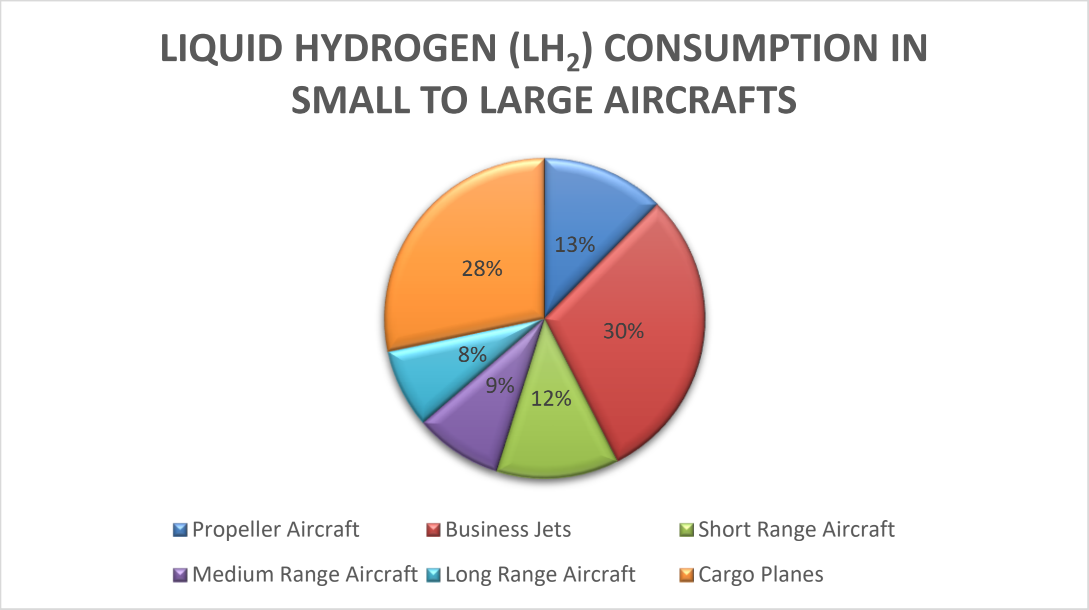
AIRLINES ADOPTING FUEL CELL TECHNOLOGY

Airlines are already attempting to match pollution reductions with their financial goals. They've promoted operational efficiency and excellent air-traffic management (ATM) and spent billions of dollars to upgrade airplanes with more efficient engines and aerodynamics made of lighter materials. Airlines should use analytics to discover areas for improvement and methodically adjust their frontline personnel’s behavior to maximize fuel economy. Plug power is one of the fuel cell manufacturing companies that integrated fuel cell technology to ground support equipment (GSE) applications and demonstrated the use of fuel cell-operated conveyor belts for loading and unloading baggage at Hamburg Airport. CO_2 capture is now a prevalent practice in the industry. The adsorption/absorption or filtering of purified CO_2 using specific materials. CO_2 is separated from the material by applying heat or electricity before it is used again. The European Union has sponsored comprehensive research aimed at determining the viability of an electric plane, a liquid hydrogen-fueled aircraft, in collaboration with 35 other enterprises led by Airbus Deutschland. Liquid hydrogen produces approximately three times the energy of kerosene, but it takes up four times the storage space. As a result, hydrogen technology for air transportation would need a significant rethinking of aircraft design, airport fuel storage technologies, and safety concerns. Governments and businesses are putting money into this opportunity. Hydrogen could also be used to power aircraft directly (hydrogen turbine) or indirectly (fuel cell). During the combustion process, hydrogen emits no CO_2 and allows for large reductions in other global warming-causing materials including soot, nitrogen oxides, and high-altitude water vapor. Airbus, the world's largest aircraft maker, is also developing a demonstration engine for use in one of its A380 superjumbo flights to demonstrate hydrogen propulsion.

NO.	**OPERATIONS**	**Liquid Hydrogen**	**Kerosene**	**Ratio**
1	Take-off weight [tons]	78	70	1.112
2	Block fuel weight [tons]	5	11	.433
3	Operating empty weight [tons]	58.5	41.8	1.362
4	Wing area [m^2]	155	113.7	1.363
5	End of cruise altitude [kft]	37.9	37.5	1.025
6	Lift/drag ratio (cruise)	18.5	17.1	.976

7	Wing loading [kg/m^2]	503.9	616.9	0.815
8	Fuselage length [m]	54	40.9	1.314
9	Energy used [kg/(seat.km)]	930	758	1.18

Comparison of liquid hydrogen and kerosene short-range aircraft



CHAPTER 9

FUTURE SCOPE AND CONCLUSION

9.1 FUTURE SCOPE

Hydrogen is the most promising fuel type we'll ever come across and it is very versatile, it can be used in many industries that support our society. Hydrogen can be used to transform our existing energy needs into a much greener and safer. Hydrogen can be vastly classified into two categories (I) Grey hydrogen is obtained from fossil fuels that result in CO_2 emissions (II) Green hydrogen is obtained from renewable resources such as solar, wind, and electrolysis but at present, these methods are expensive and require large farms to acquire hydrogen in a massive amount. It can be used in transportation, energy-producing grids, residential areas, and much more. Hydrogen is already being adopted by several car manufacturers to build eco-friendly cars that have zero impact on the environment and pack a punch as well. That allows us to travel long distances without worrying about refueling again and again. Fuel cells are another interesting invention that let us use these harmless gases to generate energy from them, the first fuel cell was commercialized in 1838 by Sir William Grove. Several car manufacturers are using fuel cells such as Toyota Mirai and Hyundai Nexo which uses a polymer electrolyte membrane fuel cell. Cryogenic technology allows us to store triple the amount of hydrogen compared to normal hydrogen compressed tanks, by storing it in a liquid state. Hydrogen along with fuel cells is gaining popularity in the aviation sector due to its outstanding performance and emission-free usage. The aviation industry reduced its fuel consumption per passenger by 39% from 2005 to 2019. According to recent studies the aviation industry managed to increase its fuel efficiency by 43% by decommissioning old aircraft and manufacturing new ones that are incorporated with stronger and lighter materials like carbon fiber (5 times stronger than steel) and installing new power-packed and fuel-efficient engines. Fuel efficiency can further be improved by optimizing flight routes. Airbus has developed three concept models surrounding hydrogen fuel cell technology and has decided to launch the first zero-emission commercial aircraft by 2035.

9.2 CONCLUSION

Hydrogen is picking up traction as we speak and is being implemented in all sectors because of its positive aspects but anything so promising has few drawbacks. We currently use grey hydrogen that is produced from fossil fuels. What we need is green hydrogen that is produced from renewable resources to power our day-to-day life to avoid polluting our environment. Fuel cells are extremely advanced technology but to manufacture one fuel cell doesn't justify the purpose of using it because they're too expensive, large positive investments must be done to minimize the cost and will encourage widespread adoption of this technology. Efficiency and performance are directly linked to hydrogen and the materials of the anode, cathode, and electrolyte. Selecting an electrolyte is very tricky because of its compatibility, operating temperatures, conductivity, and stability, all these parameters are interconnected and very important for a fuel cell. Storing hydrogen isn't a big problem but the unique properties of hydrogen make it difficult to store it in a gaseous state, so we use cryogenic technology to liquefy hydrogen at -273°C to store more hydrogen in the same capacity. Transporting hydrogen in cryogenic trailer tanks is preferred as you can carry more in one trip which can save a lot of money. Airlines like Boeing and Airbus are developing technologies that support the use of hydrogen and fuel cells, but ZeroAvia is a company solely based on hydrogen fuel cells and will launch a 100-seater commercial aircraft by 2024. Reducing the cost of fuel cells will greatly encourage governments and private sectors to implement this technology into their products, we all know that public sentiments depend heavily on the price of a product. Governments should encourage citizens to adopt this new clean fuel alternative by providing tax rebates, the Indian government is providing tax rebates of up to Rs 1,50,000. Governments must carefully place hydrogen refueling stations every 200 km by performing research and analysis and finding out what states or metropolitan areas are interested in hydrogen or fuel cell-powered cars.

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Hydrogen Fuel Cell Hybrid Technology in Aviation: An Overview

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Abstract. According to the International Air Transport Association (IATA), the industry has improved its record of fuel efficiency: fuel burned per passenger per kilometer has dropped by half since 1990. This case study aims to find a powerful and efficient propulsion system that runs on renewable resources. We'll dive deep into the study of fuel cells, particularly solid oxide fuel cells for their fuel to energy conversion ratio and close to no emissions. This study will help us understand what fuel cell design, where it'll be installed, materials of the cathode, and anode. Different materials for electrolytes will be compared to analyze each of their impact on a flight's performance which can drastically reduce the price per ticket and make air travel much more economical and environmentally clean. What storage method will be preferred for space efficiency, more capacity to reduce travel time by fueling just once, and to keep hydrogen safe from igniting itself. Fuel cells are still a work in progress due to their lack of instant power, so engineers combined them with a gas turbine creating a hybrid setup that achieves an amazing efficiency. Airlines such as Airbus, Eviation, and Zunun Aero are working on All-Electric Aircraft (AEA) where their planes are powered by hydrogen fuel cells.

Keywords: Hydrogen fuel cell, solid oxide fuel cell, fuel cell gas turbine hybrid system, liquid hydrogen, cryogenic technology.

1 Introduction

The rapid growth in aviation traffic in recent decades, as well as the expectation of continued development, has raised the demand of aircraft manufacturers to enhance aircraft economy and reduce the environmental effect. As a result, future aircraft will have to meet higher environmental criteria as well as increased economic and productivity demands.[1] These airplanes are heavy and need a very combustible fuel known as jet fuel (a blend of kerosene and, crude oil). They have found that fuel cell systems can replace present propulsion systems, hydrogen fuel cells can generate up to 300% more power from 1kg of liquid hydrogen (LH2) compared to 1kg of jet fuel. The fundamental reason to use LH2 to power airplanes is the high specific (energy/mass) heat of combustion, which is 2.8 times that of conventional fuels like kerosene. If the LH2 tank and insulation mass are a small percentage of hydrogen, the mass advantage of liquid hydrogen fuel results.[2] Fuel cells are preferred over standard Lithium-ion batteries because of their low emissions, higher efficiency, higher power density, lightweight, and less space. The main benefits of using fuel cell-powered (FCs) are that their very efficient and emit no harmful gases/emissions. The only by-product is water and heat. This literature survey helps us to conclude that solid oxide fuel cell is the best because of their operating conditions, electrolyte material, and environmentally friendly energy generation. Unmanned aircraft systems (UAS) that are powered by electricity are now used for a range of surveillance missions. Based on its high efficiency, cheap cost, and great dependability, battery systems are favoured over the usage of tiny internal-combustion engines (ICE). However, the energy density of commercial batteries limits the battery-powered unmanned aircraft systems, which has prompted the development of better FC-based systems. [3] The demonstration of an FC-system supplying supplemental power for an Airbus 320's hydraulic and electric systems and the Boeing fuel-cell demonstrator jet was demonstrated in Spain and France in February 2008 respectively. The first issue is improving energy density, which is less of an issue in other industries but critical in the aerospace industry. NASA designed FC systems for the Apollo and Gemini space missions in partnership with Pratt & Whitney and General Electric.[4] Long-range aircraft powered by kerosene and hydrogen is thus contrasted at present and future technological levels. The choice of huge long-range aircraft was made because their large fuel capacities indicate the upper limit of prospective performance gains from hydrogen adoption. The structural integrity and weight of the aircraft will drastically improve over the next few decades because of the increased use of composite materials in load-bearing structures.[5] The quantity of liquid hydrogen with the same energy content as kerosene has approximately four times the storage volume and has a significant impact on aircraft design. Liquid hydrogen cannot be stored in the same way as kerosene can and must be kept in specific tanks. To prevent liquid hydrogen from entering the gaseous phase, these tanks must have more resistance to high pressures than normal kerosene tanks and have excellent thermal insulation.[6] Liquid hydrogen is kept as a saturated liquid/gas combination at low temperatures. The interior insulation system keeps liquid hydrogen at a near-room temperature and prevents heat conduction by preventing contact between it and the tank construction (a) the tank pressure must be greater than atm pressure to avoid air ingestion, which might result in an explosion. (b) fuel tanks must be designed for long periods due to maintenance issues.[7] Metal hydrides are also be used to store gaseous hydrogen, for a venting pressure of 2 bars against 1 bar the tank volume must be raised by 5%. An ellipsoid promises highly adaptable geometric designs that include ellipsoidal heads and elliptical shells. For the needed internal pressures, which are twice as higher as regular cryogenic systems in terms of magnitude, the tank-wall thickness increases dramatically. [8-9] The cryogenic tank requires some energy to convert the phase of the hydrogen and to warm it to ambient temperatures. The enthalpy of vaporization for LH2 is 20K is 450kJ/kg and specific heat is 13.68kJ/kg/K.

Table 1. Energy consumption for a tank's production

MATERIALS	WEIGHT (kg)	ENERGY CONSUMED (MJ/kg)	TOTAL (KGJ)
Aluminium	14.9	219.5	3.4
Polyester	6.9	169	1.275

One of the most important characteristics of a propulsion system is energy production in a particular amount of fuel ($Whkg^{-1}$). Researchers have proposed an experimental setup that has a fuel cell and gas turbine to work in a programmed and timely fashion where the fuel cell (will deliver instant power) while take-offs and the gas turbines operate to keep the plane moving while the fuel cell supports the gas turbine whenever there is a power lag from the gas turbine. To safely store hydrogen, we use cryogenic tanks that maintain a chilling temperature of -273°F (169.4° C) to keep hydrogen in a liquid state, it saves a lot of space and allows you to store more liquid hydrogen for long duration flights.

Table 2. Past studies on hydrogen production (in chronical order)

year	USA	CHINA	SPAIN	JAPAN	OTHER COUNTRIES
2005-	Fuel Cell – 12	Steam	Ethanol steam	Steam	Steam reformation

2009		reformation – 14	reforming – 6	Reformation - 13	– 70
2009-2013	Fuel Cell - 13	Biohydrogen production – 17	Decomposing methane - 13	Water splitting - 11	Steam reformation - 84
2013-2017	Photocatalysis - 15	Photocatalysis - 113	Steam reformation-11	Steam reforming - 9	Photocatalysis - 329

As seen in table 1 steam reforming was a popular method to produce electricity and even to produce hydrogen which is not a clean method to produce hydrogen. Steam reforming has been around for the past 40 years and has been a valuable commercial fuel, the primary gas produced during the process depends on the operating temperatures, pressures, steam, and carbon feed rates. Two extreme steps in steam reforming are (i) reducing gas production which involves primary steam reforming at high temperatures (982°C or higher) (ii) substituting natural gas (SNG) production that requires steam reforming at the highest pressure.[11]

Photocatalyst consists of two words a photon and a catalyst (which alters the speed of a chemical reaction). Photocatalysts are substances that accelerate/decelerate the rate of a chemical reaction on exposure to light. This phenomenon is called photocatalysis. Photocatalysis is the reactions that take place by utilizing a semiconductor and primarily light.[12]

2 Hydrogen

Hydrogen is a primary element and is present in every inch of the universe, hydrogen occurs in a gaseous state. It can be manufactured through several methods: methane gas, reforming, coal gasification, and water electrolysis. Green hydrogen is the best type of manufactured hydrogen where water electrolysis is used to separate two water molecules and one molecule of hydrogen. Hydrogen gas can be used in typical gasoline-powered internal combustion engines with a few modifications, but it emits nitrogen. PEM is the most researched fuel cell which eventually was installed in FCVs. The proper utilization of renewable energy sources will enable us to manufacture hydrogen that can be emissions-free. The present focus is on hydrogen as a low-emission alternate fuel, the probability of hydrogen becoming the next all-rounder fuel is very high due to its power output, efficiency, and applications. It will be the principal energy source that will be supplied to houses, manufacturing plants, vehicles, etc. [13]

Table 3.COMPARISON OF HYDROGEN TO OTHER FUELS

Types of Fuel	The energy produced per unit mass (J/Kg)	The energy produced per unit volume (J/m^3)	Carbon emission specific (kg/kg fuel)

Hydrogen gas	143	0.014	0
Liquid hydrogen	143	10.11	0
Fuel oil	44	38.6	.85
Gasoline	46	38.65	.84
Jet fuel	45.50	34.85	-
Liquefied petroleum gas	48	35.30	-
Liquefied natural gas	50	24.40	-
Methanol	22	23	.50
Ethanol	29	18.10	.50
Biodiesel	37	23.60	0.51
Natural gas	51	33	0.47
Coal	31	-	0.50

2.2. properties of Hydrogen

Hydrogen does not occur naturally, it can be created through a variety of methods, including water electrolysis, methane gas reforming, and coal gasification. Hydrogen has a lot of energy, and an engine that runs on it creates nearly few emissions. Hydrogen is a colourless, odourless gas that makes up 75% of the mass of the universe. It is found on Earth in the presence of other elements like oxygen, carbon, and nitrogen. Hydrogen derived from renewable energy sources is a nearly unlimited and ecologically friendly energy source that could fulfil the majority of our future energy requirements. In its solid state, hydrogen has the potential for extremely high energy densities, which are important for mobile applications.[15]

Table 4. Chemical properties of Hydrogen

NO.	PROPERTIES	VALUES	UNITS
1.	Molecular weight	2.015.5	Amu
2.	Density (Gaseous)	0.0837.5	kg/m3
3.	High heating values	141.90	MJ/kg
4.	Low heating values	119.90	MJ/kg
5.	Temperature (boiling)	20.4	K
6.	Density (liquid)	7	Kg/m3
7.	Critical point pressure	1283	kN/m2
8.	Critical point temperature	32.95	K
9.	Critical point density	30	kg/m3
10.	Temperature (self-ignition)	859	K
11.	Temperature (flame)	2318	K

2.3 Hydrogen Economy

Based on intense and optimistic research, hydrogen and fuel cells will meet the global energy demands by 2050. To supply large amounts of hydrogen to every place, we've to build tiny hydrogen production sites. The price of hydrogen produced from natural gas steam reforming is currently much lower than hydrogen production through electrolysis. Production of hydrogen cost is currently lowest in large, centralized gas reformers and is highest in an electrolyser system. An electrolyser is a device that needs an electric current to segregate water into oxygen and water in a process called electrolysis.[17] Electrolyzers are projected to have large learning effects, and electricity prices from various renewables could be very low if hydrogen synthesis occurs during times of abundant electricity. The comparatively low production costs of natural gas are a primary reason for its present widespread use in hydrogen production. Fuel cell vehicles and hydrogen mobility are still prohibitively expensive compared to conventional gasoline-powered cars and alternatives like rechargeable electric vehicles.[18] The future of renewable hydrogen production is based on the country's financial position and the government's willingness to work to pass bills for the reduction of fossil fuel consumption. The hydrogen economy rises when hydrogen is produced through renewable resources such as solar energy, geothermal, or biomass due to their cost-effective nature. Japan is one of the most technologically advanced countries and is motivated in Asia to develop and change the renewable hydrogen economy in the long term.

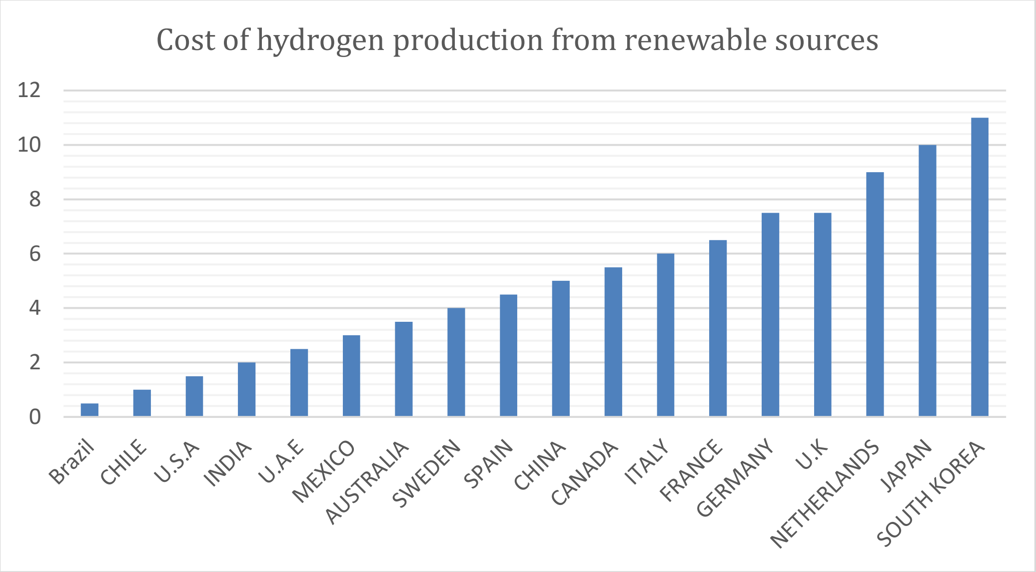

Fig.1. Cost of Hydrogen production from renewable sources Dollar per kg hydrogen as per 2020

Hydrogen production in the short term is through electrolysis and natural gas reforming, they're also considering biomass to produce hydrogen and their strategy for storage is to use compressed tanks for the short term and liquefication of produced H_2 gas for the long term.[19]

3 Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cells are installed in stationary power generators, airplanes, and military equipment because of their low emissions, higher efficiency, fuel flexibility, and less noise. A solid oxide fuel cell is a high-temperature operating fuel cell from 600°C to 1000°C and that's why we can use inexpensive catalysts like platinum, or rhodium. The process of commercializing solid oxide fuel cells is difficult because of its short lifetime and therefore increases its maintenance cost. To achieve absolute adoption of solid oxide fuel cells, we reduce system cost, improve system performance, and develop new strategies to diagnose faults and improve the fuel cell.[20] Efficiency is one of the main advantages because solid oxide fuel cells are installed in fuel cell vehicles. The efficiency achieved is 100% when we use dry methane, unlike hydrogen or carbon monoxide only 70% efficiency is achieved. This would force car manufacturers to completely change their car's design by installing a bigger fuel cell that provides higher power output and is appropriate for a long-distance journey. Improving internal reforming can reduce the number of oxidants used while oxidation on the anode side will improve the efficiency.[21]

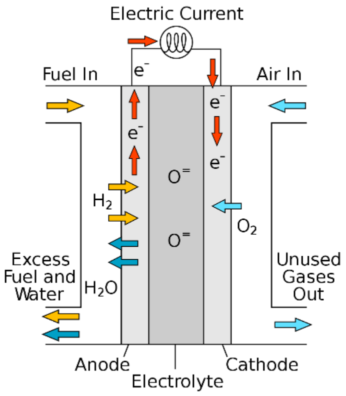

Fig 2. Solid Oxide fuel cell working principle

3.1 Principle

A solid oxide fuel cell (SOFC) consists of an anode, cathode, and electrolyte. It converts the chemical energy into electricity through an electrochemical reaction and has close to no emissions. A solid oxide fuel cell-based cathode, a nickel oxide-based anode, and an oxygen ion or proton-conducting oxide-based electrolyte normally make up a single sofc. Solid oxide fuel cell differs from fuel cells that operate at low temperatures like proton exchange membrane fuel cells (PEMFC) at room temperature to 80 °C by fuel flexibility which requires an operational temperature (400-1000°C).[22] The electrodes are solid porous surfaces that allow fuel and air to diffuse into the electrolyte while allowing the electrochemical reaction products on the anode side to diffuse away from it. The O_2 ions generated by the reduction of molecular oxygen (at the cathode) are carried from the cathode to the anode of the solid oxide fuel cell by the electrolyte. Fuel diffuses through anode/electrolyte contact through the anode. It catalyzes the reaction with the oxygen ions, releasing electrons that are carried via an external circuit and converted to electricity. Individual cells are electrically connected in series with a metallic connector to improve voltage and power, and they can be stacked to produce the best stack size.[23]

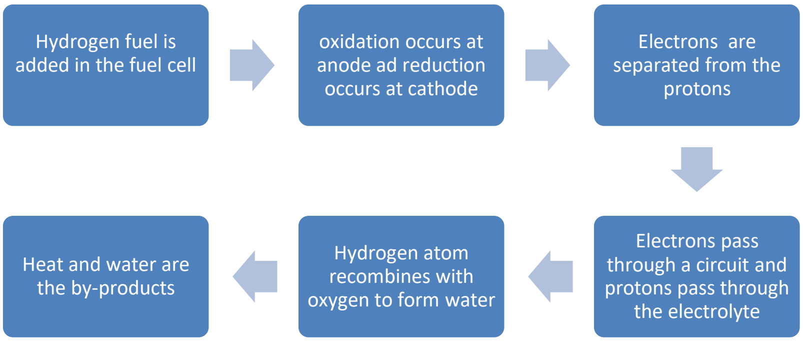

Fig.3. Working of a fuel cell

3.2 Performance

Solid oxide fuel cell (SOFC) has a higher power conversion ratio and current density compared to other fuel cells. Small stationary solid oxide fuel cell systems in the 1–100 kW power range achieve an electrical net efficiency of up to 50% and operate between (850°C to 950°C). We're mainly focusing on sofc as a propulsion system for aircraft, solid oxide fuel cells are perfect for aviation due to their efficiency and regular functioning at high altitudes. The take-off in an aircraft is the most energy-consuming task and a fuel cell like any other electronic device cannot function at its peak all the time, so we use a power management system that steps in and solves the issue of lack of instantaneous power. The PMS uses a Lithium-polymer battery that generates a maximum power of 300W, and the batteries store the surplus power generated by the fuel and use it when the fuel cell is not working at its peak.[24] Aside from tiny, combined heat and power generation systems (PMS) for residential areas are also using solid oxide fuel cells. Most consumers don't know that stacking solid oxide fuel cells in a tubular form can avoid sealing and corrosion.[25] SOFCs are versatile due to their flexibility in using any fuel like methane, natural gas, biogas, and hydrogen. An electrolyte is the heart of a fuel cell and selecting the right electrolyte can give you the best performance and highest efficiency. The materials should be compatible with electrodes such as cathode, and anode and should also be mechanically and chemically stable.[26] Lanthanum Gallium Oxide ($LaGaO_3$) based electrolyte is one of the few major advancements in fuel cell research, the reason why researchers think it has so much potential is because of its greater oxide-ion conductivity than too at low temperatures. [27] A recent experiment showed us that ammonia (NH_3) is a better hydrogen carrier, NH_3 is easier and faster to liquify than hydrogen at an ambient temperature of around -33°C under 10 atm pressure, and the volumetric energy density (9×10^6 kJ m^{-3}) is higher (than hydrogen) makes it easier to store and transport. Ammonia is less flammable than hydrogen and can be easily detected by the human ear and the nose because of its distinct smell.[28]

Table 5. **Types of Electrolytes**

Properties	**Yttria stabilized Zirconia (YSZ)**	**Dopped Gadolinium Ceria (GCO)**	**Lanthanum gallate (LSGM)**	**Scandium-Stabilized Zirconia (ScSZ)**
Compatibility	Excellent stability in oxidizing,Reduces environmental damage	Great compatibility with cathode material	Great compatibility with cathode materials	Great stability in oxidizing and reducing environmental

				damage.
Stability	Great Mechanical stability	At low pO_2, a mixed electronic-ionic conductor is formed		better long-term stability than Yttria stabilized zirconia (YSZ)
Practical applications	Most of the solid oxide fuel cells use YSZ electrolyte		Ga-evaporation at a low partial pressure of oxygen	Availability and price of scandium
Conductivity	Low ionic conductivity (especially YSZ)	Electronic conduction at PO_2 → low Open circuit voltage	Incompatible with NiO	
Temperature	800°C - 1000°C	600°- 800°C	1000°-1200°C	450°C- 550°C

4. Storage

Today's global economy is built on free energy that has been naturally stored for millions of years. Hydrogen is a renewable and environmentally acceptable fuel. The storage of hydrogen on a large scale is a significant difficulty with existing technology, storing, and transporting hydrogen is extremely challenging. Hydrogen has the highest heating value per unit mass. The volumetric density of liquid hydrogen is 70.8 kgm^3, and in large volumes with low thermal losses, hydrogen can achieve a system mass ratio close to one. Metal hydrides have the highest volumetric densities of hydrogen. Many metals and alloys can absorb substantial amounts of hydrogen reversibly.[30] The most common storage method is a high-pressure gas cylinder with a maximum pressure of 20 MPa. Inexpensive, light, excellent adsorption, desorption kinetics, and recyclability are all characteristics of good H_2 storage materials.

4.1 Storage options

1. Compresses gaseous hydrogen (CGH_2) storage system is large and tough to accommodate within a compact vehicle. The cost of the enormous storage tanks required for a 500-kilometer range is high because of the number of strong materials (composite, metal) required.
2. Although the liquid hydrogen (LH_2) storage system is high in density and relatively inexpensive, we face evaporative losses just after 3 days of idle usage. Total consumption for liquid hydrogen storage is about 35% of the stored hydrogen, which is lost more. Austenite material stainless steel is used to manufacture cryogenic tanks because of its quality to insulate gases at low temperatures.[31]

A new type of storage method is currently being used in Germany, U.K, U.S.A, and Canada, the manufactured hydrogen is stored in artificially created caverns. The caverns are covered with salt because it does not react with hydrogen because of their inert nature. These caverns are built 400m below the ground and their total volume is 200,000m^3, these caverns are naturally good at storing hydrogen gas because the large rock salt prevents its escape. [32]

Researchers have combined these two technologies to improve storing hydrogen for stationary purposes and automobile industry, a cryogenic pressure vessel (CPV) is made up of an inner vessel with high pressure built of carbon-fiber-coated metal (like those used for compressed gas storage), a vacuum space filled with multiple sheets of highly reflective metalized plastic (for high-performance thermal insulation), and a metallic outer shell. Cryogenic vessels work at low temperatures (approx. 20K) and high pressures (360 bar), holding hydrogen at a far higher density than compressed gaseous hydrogen.[33]

Table 6. Types of Hydrogen Storage in Different States

	Category	**Type**
1	Chemical storage (metal hydride)	Magnesium hydride (MgH_2), Sodium hydride (NaH), calcium hydride (CaH_2)
2.	Physical storage (metal-organic framework)	PCN-6 PCN, porous coordination network
3.	Gas Storage	Compressed H_2
4.	Liquid hydrogen	Liquid hydrogen (LH_2)

4.2 Challenges

Hydrogen is a very light fuel (7% density of air) and 12x as diffusive as gasoline. Hydrogen-catching fire or exploding is rarely seen as a hydrogen-air mixture has a higher chance to ignite. Hydrogen storage is the most important aspect of a country's hydrogen economy. Hydrogen has extremely low density, a storage tank is installed to mimic a 400km distance journey, 8kgs of hydrogen for an internal combustion engine (ICE), or 4kgs of hydrogen for a fuel cell. The most common method currently used is compressed gaseous hydrogen (CGH_2). The three issues at hand are finding an ideal storage material that checks out all three requirements: high hydrogen density, fast release with minimum energy barriers, and reversibility of the release cycles at normal temperatures (70-100°C) must be compatible with a fuel cell. Gravimetric and volumetric density is very important in both stationary and mobile applications. The best way to store hydrogen is through cryogenic tanks, which cool down hydrogen down to (-259°C) that enabling us to store more because hydrogen occupies less space, but these tanks require a constant electricity supply to maintain the freezing temperature and regular maintenance.[35]

5. Fuel Cell-Gas Turbine Hybrid Technology (Fc-Gt)

The gas turbine is a rotary engine that uses a flow of combustion gases to extract energy (which produces 10Whkg-1). Ambient air is taken into the engine intake, where it is boosted in pressure and temperature by an axial or centrifugal compressor (or both) before being fed into the combustion chamber. Fuel is mixed with hot compressed air and ignited in the combustion chamber. It is self-sustaining once it has ignited because the steady flow of oxygen and fuel ensures that combustion continues. The aviation industry reduced fuel consumption by 70% while simultaneously reducing noise generated by the engine and cutting gaseous carbon monoxide and hydrocarbon emissions by around 50% and 90%, respectively, over the past 40–50 years. This is all thanks to technological advancements in materials and cooling that allow engines to operate at turbine entry temperatures (TET) and high overall pressure ratios (OPRs) and improve thermal efficiency, which reduces the engine's specific fuel consumption (SFC) for cost savings.[36] To achieve better results, we have combined both to produce half of the power resulting in a lightweight fuel cell system where it weighs less and is more efficient and works simultaneously with a gas turbine (which produces 10Wh in 1Kg of jet fuel) and works at an efficiency ranging between 30% to 50%.[37]

Table 7. Liquid Hydrogen in Aviation

Areas of Effect	Advantages of Liquid hydrogen	Disadvantages of Liquid hydrogen
Combustion	Higher specific energy (119190kJ/kg), higher efficiency, higher combustion temperature	Four times lower energy/unit volume
Aircraft Design	Reduced gross weight by 26%, Weight reduced from wings by 18%. Smaller engines and reduced noise, Cruise's lift/drag ratio reduced by 15%	With the more voluminous fuselage, you've to install a cryogenic fuel system
Airport	Airports will have hydrogen production	The amount of hydrogen

infrastructure	facilities on-site for faster refueling time for planes and other support vehicles	stored for refueling
Emissions	No emissions of carbon monoxide, carbon dioxide	

6. Efficiency at High Altitudes

6.1. Efficiency of Conventional Jet Engines

The efficiency of a conventional aircraft is 43.1% during cruise whereas an all-electric aircraft (AEA) has an efficiency of 66.1% during the cruise. The standard carbon dioxide (CO_2) is 3148 CO_2/kg fuel, AEAs are desirable for short-range because of these 800-2000Wh/kg case scenarios we only evaluate the efficiency for 500 miles.[39]

A traditional aircraft uses a mixture of kerosene and crude oil, popularly known as jet fuel. The gases emitted by burning kerosene are NO_x, $CO_{2,}$ and H_2O in the air. Emission rates after burning kerosene are 3.18g of CO_2/kg, besides emission rates kerosene per kg is $1.08. Looking at all the values and results, it’s safe to say that aircrafts powered by renewable sources like fuel cells are the future. The sound produced by these humongous engines of a Boeing 747-400 was 91.6 dBA [40]

6.2 EFFICIENCY OF AIRCRAFT POWERED BY HYDROGEN FUEL CELL

Liquid hydrogen has caught everyone’s attention by being the most versatile clean fuel for all purposes because of its specific volume. Liquid hydrogen requires a larger carrying capacity than conventional jet fuel. Designers have issues with hydrogen fuels in terms of mass and volume requirements and fuel management and storage onboard planes. The adoption of liquid hydrogen is a 30% reduction in the aircraft’s gross weight compared to kerosene. A long-range liquid hydrogen-powered aircraft is 7 meters longer than usual. A liquid hydrogen aircraft reduces the volumetric capacity for payload.[41] The fuel cells are stacked in a tabular form to save space and add more FCs (if necessary), maintaining a fuel cell stack’s temperature is important as it directly impacts the performance. When the fuel cell stack’s temperature is too low, a longer time is taken to start a fuel cell and mass transport has the highest potential. When the temperature is too high the self-humidification function begins to break down, and a lack of water reduces the conductivity of a fuel cell membrane.[42]

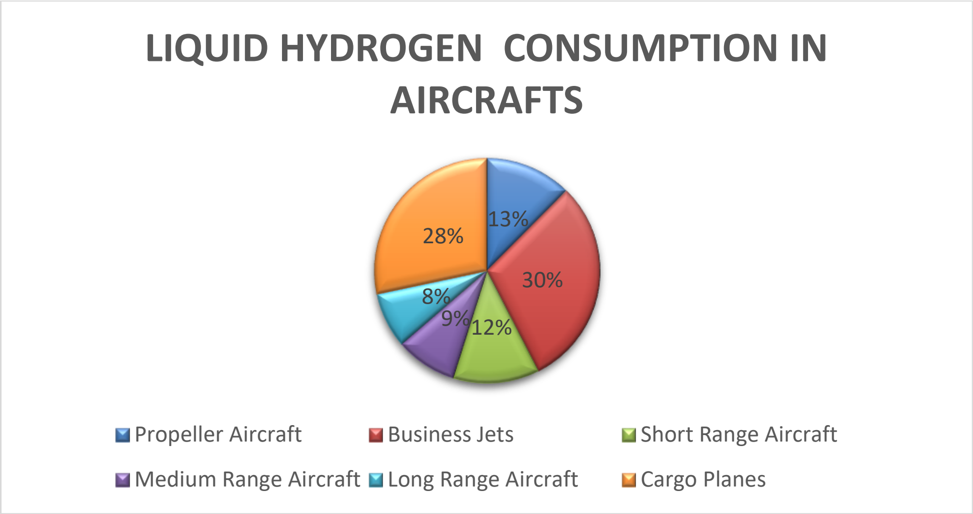

Fig.4. Liquid Hydrogen Consumption in different types of Aircrafts

Table. 8. Comparison of Liquid Hydrogen and Kerosene in Short-Range Aircraft

Sr. No.	**OPERATIONS**	**Liquid Hydrogen**	**Kerosene**	**Ratio**
1	Take-off weight [tons]	78	70	1.112
2	Block fuel weight [tons]	5	11	.433
3	Operating empty weight [tons]	58.5	41.8	1.362
4	Wing area [m^2]	155	113.7	1.363
5	End of cruise altitude [kft]	37.9	37.5	1.025
6	Lift/drag ratio (cruise)	18.5	17.1	.976
7	Wing loading [kg/m^2]	503.9	616.9	0.815
8	Fuselage length [m]	54	40.9	1.314
9	Energy used [kg/(seat.km)]	930	758	1.18

7. Airlines Adopting Hydrogen Fuel Technology

Airlines are already attempting to match pollution reductions with their financial goals. They've promoted operational efficiency and excellent air-traffic management (ATM) and spent billions of dollars to upgrade airplanes with more efficient engines and aerodynamics made of lighter materials. Airlines should use analytics to discover areas for improvement and methodically adjust their frontline personnel’s behavior to maximize fuel economy. Plug power is one of the fuel cell manufacturing companies that integrated fuel cell technology to ground support equipment (GSE) applications and demonstrated the use of fuel cell-operated conveyor belts for loading and unloading baggage at Hamburg Airport. CO_2 capture is now a prevalent practice in the industry. The adsorption/absorption or filtering of purified CO_2 using specific materials. CO_2 is separated from the material by applying heat or electricity before it is used again.[45] The European Union has sponsored comprehensive research aimed at determining the viability of an electric plane, a liquid hydrogen-fueled aircraft, in collaboration with 35 other enterprises led by Airbus Deutschland. Liquid hydrogen produces approximately three times the energy of kerosene, but it takes up four times the storage space. As a result, hydrogen technology for air transportation would need a significant rethinking of aircraft design, airport fuel storage technologies, and safety concerns.[46] Governments and businesses are putting money into this opportunity. Hydrogen could also be used to power aircraft directly (hydrogen turbine) or indirectly (fuel cell). During the combustion process, hydrogen emits no CO_2 and allows for large reductions in other global warming-causing materials including soot, nitrogen oxides, and high-altitude water vapor.[47] Airbus, the world's largest aircraft maker, is also developing a demonstration engine for use in one of its A380 superjumbo flights to demonstrate hydrogen propulsion.

ZEROAVIA-After successfully testing a 6-seater last fall, ZeroAvia gets a head start on hydrogen-electric flying for smaller aircraft. The test flight was another step in the road that appears to put ZeroAvia on pace to launch a 10- to 20-seat aircraft with a 520-mile range into the market in 2024.[48] The company has recently signed a deal with Shell to develop a compressed, low carbon hydrogen supply for its facility in California. Additionally, Shell will support the development of ZeroAvia's hydrogen flight test programme.

8. Future Scope and Conclusion

8.1 FUTURE SCOPE

Hydrogen is the most promising fuel type we'll ever come across and it is very versatile, it can be used in many industries that support our society. Hydrogen can be used to transform our existing energy needs into a much greener and safer. Hydrogen can be vastly classified into two categories (I) Grey hydrogen is obtained from fossil fuels that result in CO_2 emissions (II) Green hydrogen is obtained from renewable resources such as solar, wind, and electrolysis but at present, these methods are expensive and require large farms to acquire hydrogen in a massive amount. It can be used in transportation, energy-producing grids, residential areas, and much more. Hydrogen is already being adopted by several car manufacturers to build eco-friendly cars that have zero impact on the environment and pack a punch as well. That allows us to travel long distances without worrying about refueling again and again. Fuel cells are another interesting invention that let us use these harmless gases to generate energy from them, the first fuel cell was commercialized in 1838 by Sir William Grove. Several car manufacturers are using fuel cells such as Toyota Mirai and Hyundai

Nexo which uses a polymer electrolyte membrane fuel cell. Cryogenic technology allows us to store triple the amount of hydrogen compared to normal hydrogen compressed tanks, by storing it in a liquid state. Hydrogen along with fuel cells is gaining popularity in the aviation sector due to its outstanding performance and emission-free usage. The aviation industry reduced its fuel consumption per passenger by 39% from 2005 to 2019. According to recent studies the aviation industry managed to increase its fuel efficiency by 43% by decommissioning old aircraft and manufacturing new ones that are incorporated with stronger and lighter materials like carbon fiber (5 times stronger than steel) and installing new power-packed and fuel-efficient engines. Fuel efficiency can further be improved by optimizing flight routes. Airbus has developed three concept models surrounding hydrogen fuel cell technology and has decided to launch the first zero-emission commercial aircraft by 2035.

8.2 CONCLUSION

Hydrogen is an abundant fuel and has no negative effects on the environment, two types of hydrogen are blue hydrogen is produced from fossil fuels that have emissions whereas green hydrogen is produced from renewable sources that are environmentally safe. To use that hydrogen fuel cells are used for their features of high performance, one-time investment, and emit no global warming gases. Fuel cells are being used in vehicles, spacecraft, industrial heavy vehicles, etc. Fuel cells are an amazing technology that offers performance, and efficiency and is environmentally friendly. Hydrogen storage is still difficult whereas traditional tankers are risky for storing H_2 due to hydrogen’s low volumetric energy density. The tank’s pressure must be higher than the atmospheric pressure. Transportation is another problem since hydrogen has a lower viscosity and density it is more prone to leakage but that can be solved by using the existing gas pipeline to supply it to industries and domestic homes. With time and technology, progress in harnessing hydrogen’s true potential can be easy and that solves all the problems from stationary to transportation. Car manufacturers such as Toyota, Hyundai, and General Motors have invested in fuel cell technology and have manufactured commercial-grade vehicles which are quite popular. Short-range aircraft can already be powered by a fuel cell stack and are now moving on to long-range aircraft. There is a lot of potential in hydrogen and technologies

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