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Hydrogen-Enriched Combustion in Internal Combustion Engines for Enhanced Efficiency and Emission Reduction

[1]Piyush Jha, [2]Sahil Mayank, [3]Sanyam Jain
Delhi Technological University

Abstract

Introduction of hydrogen into IC engines as an additive is considered as one of the most promising ways to develop efficient low-emission systems. The present work describes an analysis of hydrogen-assisted combustion in SI and CI engines regarding the improvement of engine performance and reduction of harmful emissions. Due to hydrogen's high flame propagation velocity, flammability limits, and carbon-free nature, it allows for the acceleration of combustion processes and the minimization of the influence of cyclic variations.

The paper investigates several methods of hydrogen input into engines, such as port fuel injection, direct injection, and mixing of hydrogen with standard fuels. Hydrogen addition increases the speed of combustion, improves the thermal efficiency, and lowers carbon-containing pollutants such as CO_2, CO, and HC. However, the increase of the combustion temperature can lead to an increase in the concentration of nitrogen oxides. It can be managed by means of lean combustion and EGR.

Challenges like pre-ignition, backfiring, hydrogen storage capacity, and safety issues are also analyzed extensively. The research concludes that hydrogen-fueled internal combustion engines are technically feasible and economically viable transitional options that will enable decarbonization partially and utilize the available engine technology base. This represents a feasible option that can reduce carbon emissions until the adoption of sustainable and emission-free transportation solutions becomes possible.

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I. INTRODUCTION

In today's day and age, the transportation sector relies heavily on the consumption of energy from conventional sources to meet global demands because of the ever-increasing global population. The transportation sector is the largest emitter of greenhouse gases and heavily depends on fossil fuels. Fossil fuels are a necessity for transportation equipment to operate; in fact, such equipment utilizes a significant portion of energy extracted from fossil fuel sources globally. These fossil fuels account for 25% of global emissions, resulting in environmental issues such as air pollution and global warming. There is increasing pressure on the transportation industry to become more efficient and reduce greenhouse gases emissions.There is the need to minimize pollution resulting from the use of the internal combustion engine.There is danger to both people and the environment when there are harmful emissions coming out of the engine such as smoke, CO, unburnt hydrocarbons, particulate matter and NOx.Since fossil fuels are finite,there is an energy crisis resulting from depletion of fossil fuels. Therefore, in order to solve this problem,scientists have to do extensive research on the use of alternative renewable fuels that will help meet the environmental challenges. There is the need to find new sources of energy due to the increasing pressure for environmental protection and energy efficiency.

Cutting down the carbon footprint of transport systems is essential to achieving sustainable objectives.Awareness of the necessity for a sustainable source of energy in the automobile industry has spurred extensive research and development in finding alternative energy sources, which is essential for ensuring the future safety and viability of IC engines.Nevertheless, owing to their flexibility, IC engines will continue to dominate the power and transport industries.In fact, several studies have tried to design a proper combustion system that ensures complete combustion of hydrocarbon fuels, but the problem remains unresolved.

1.1 MOTIVATION

Developing alternative sources of energy has become necessary since reducing greenhouse gas emissions and dependence on fossil fuels have become increasingly important. Despite the growing popularity of electric vehicles, the market is mostly still based on internal combustion engines (ICEs), especially for large equipment, off-road machinery, and remote locations. Considering its abundance, ease of integration into ICE platform, and the absence of carbon compounds, hydrogen is an excellent fuel candidate in this regard.

Unique burning properties of hydrogen such as fast flame speed, wide flammability range, and cleanliness provide the possibility of improving the thermal efficiency and drastically decreasing emissions of existing engine designs.

Investigation of application of hydrogen in internal combustion engines (ICEs) is an alternative decarbonizing pathway, which does not involve a complete overhaul of the current automotive industry. In addition to that, hydrogen can function as a transition technology before the implementation of hydrogen fuel cells. The possibility of preserving benefits of ICE design, including ruggedness, convenience, and technological readiness while addressing the problem of their negative impact on the environment is the primary motivation for this research.

1.2 SIGNIFICANCE

As part of the world's efforts in moving towards greener energy sources, the study of hydrogen as an ICE fuel is highly necessary. The reduction of greenhouse gases produced by the transport sector, particularly automobiles, has become an urgent priority due to environmental concerns. As hydrogen can be used as a zero-emission fuel that does not emit CO_2, it can greatly reduce or even eliminate carbon emissions from ICEs, which have been primary sources of carbon emissions.

Since the research revolves around the application of hydrogen fuel in existing ICEs, the significance of this study is heightened by its ability to leverage the existing infrastructure, technology, and investments established for ICEs. In scenarios where electrification is challenging to implement, such as heavy machinery, agricultural, and remote locations, hydrogen-based ICEs serve as a bridge to transition away from traditional engines without the need for entirely new systems and logistics as seen in fuel cell vehicles and BEVs.

Furthermore, studies on hydrogen combustion in internal combustion engines (ICEs) provide insights into optimizing engine performance and minimizing NO_x emissions.

Additionally, researching hydrogen combustion in internal combustion engines (ICEs) offers important information about enhancing engine performance, increasing efficiency, and reducing nitrogen oxide (NO_x) emissions. The findings of this study have the potential to significantly advance national and international clean energy goals, promote energy diversification, and hasten the adoption of low-emission technologies.

II. LITERATURE REVIEW

2.1)Fuel Properties of Hydrogen

1)Flame Speed

At stoichiometric ratio, hydrogen shows a very high laminar flame speed in comparison to other fuels.Because hydrogen burns more quickly than gasoline, an engine running on hydrogen has a brake thermal efficiency that is six times higher than an engine running on gasoline.Because of its increased thermal efficiency and power production, this high flame speed has the potential to improve and accelerate combustion.Because of the rapid spread of hydrogen flames, engine designs must be carefully regulated to prevent pre-ignition and knocking.

2)Diffusivity

For hydrogen, diffusion is very high. It is a general fuel dispersion characteristic. Compared to gasoline, hydrogen is more beneficial and has a higher diffusivity. The hydrogen facilitates better air-fuel formation and a more homogenous mixture.This suggests that hydrogen spreads and mixes quickly with air. This characteristic makes it easier for a more homogeneous air-fuel mixture to form, which improves combustion efficiency.The disadvantage is that hydrogen storage device leaks can explode if they build up in small areas and have a short environmental half-life.

3)Density

The lightest element is hydrogen, which requires storage at extremely low temperatures or high pressures to provide an energy density comparable to liquid fuels because it has a low density when it is gaseous.The low volumetric energy density of hydrogen, even in its most compressed or liquid condition, makes storage and transportation challenging.

4)Autoignition Temperature

The minimum temperature at which a substance can ignite on its own without the assistance of a flame or other outside energy source is known as auto ignition temperature. The auto-ignition temperature of hydrogen prevents premature ignition. The greater ignition temperature of hydrogen allows for large compression ratios that are not possible in traditional engines.Compared to gasoline, hydrogen has a substantially higher value.Hydrogen is a little safer fuel for internal combustion engines due to its greater autoignition temperature, which reduces the possibility of the engine being knocked or uncontrollably ignited.

5)Ignition Energy

In comparison to gasoline, hydrogen exhibits an extremely low minimum ignition energy, roughly ten times lower.Because hydrogen can be ignited by minimal energy sources like static electricity or little sparks, it needs to be handled, stored, and used with caution at all times. Premature ignition is a serious performance issue with hydrogen due to its reduced spark energy for spark ignition due to a lower minimum ignition source energy..

6)Flammability Range

Hydrogen has the most diverse spectrum of flammability of all fuels. As a result, hydrogen can burn in a range of fuel-air ratios in internal combustion engines, making it appropriate for lean-burn tactics that increase fuel efficiency and lower emissions of nitrogen oxide (NOx). A car that runs on a lean mixture typically burns fuel more efficiently and has a fuller combustion reaction.

Properties	Hydrogen	Petroleum	Diesel	References
Ignition Energy(MJ)	0.02	0.25	-	[2],[3],[4],[5],[6]
Auto-ignition temperature(K)	858	500-750	553	[2],[3],[4],[5],[6]
Density(Kg/mol)	0.08	720-775	833-881	[2],[3],[4],[5],[6]
Flame Speed(m/s)	2.65-3.25	0.37-0.43	0.35-0.4	[2],[3],[4],[5],[6]
Flame temperature(K)	2207	2307	2327	[2],[3],[4],[5],[6]

Table 1: Explaining Flammability Range of fuel

2.2) Carbon Cycle

Despite the fact that the temperature of the sun has been increasing over time, the climate of the earth is observed to be extremely stable, which is strongly connected to the carbon cycle.

The total amount of carbon dioxide can be divided into three separate reservoirs within Geological time. Our atmosphere acts as a link between these three reservoirs because they undergo various chemical reactions over time, leading to the formation of a cyclic pattern of the amount of carbon dioxide in our atmosphere. These three reservoirs include The Ocean, The Land, and The Solid Earth. This relationship can be better understood by looking at the diagram provided below.

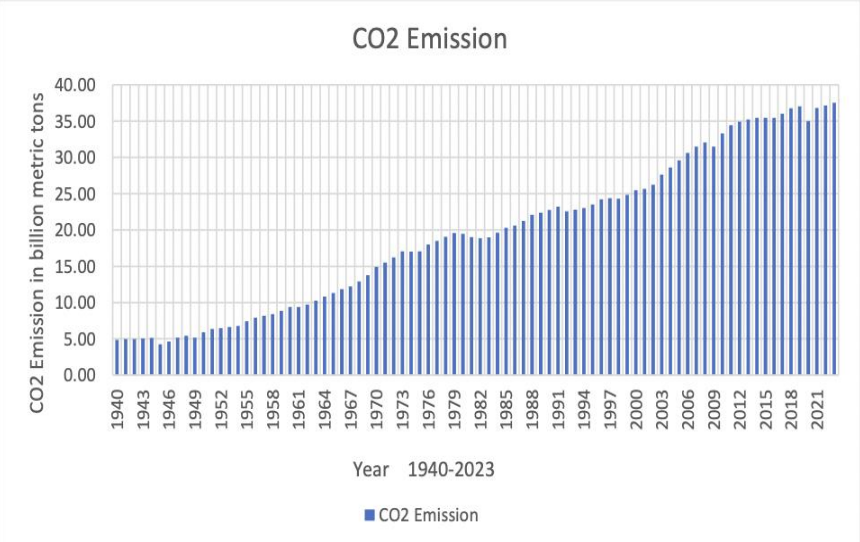


Figure 1. CO2 Emission VS Year

2.3) Effect of Hydrogen Fuels on Internal Combustion (IC) Engine Performance and Emission (Analysis)

Brake Thermal efficiency

The brake thermal efficiency is defined as a measure that represents the extent to which an internal combustion engine converts the energy stored in the fuel into mechanical energy of the crankshaft. It is very important to measure this because it provides information about the overall efficiency of the engine.An engine with a higher brake thermal efficiency uses more energy from the fuel in producing work.

When hydrogen is introduced in the engines, the brake thermal efficiency becomes lower. This is because the high amount of energy per unit volume and the faster burning rate of hydrogen improve the efficiency of the engine.It was found that M10-hydrogen and E10-hydrogen have high brake thermal efficiency compared to gasoline but not as high as hydrogen.

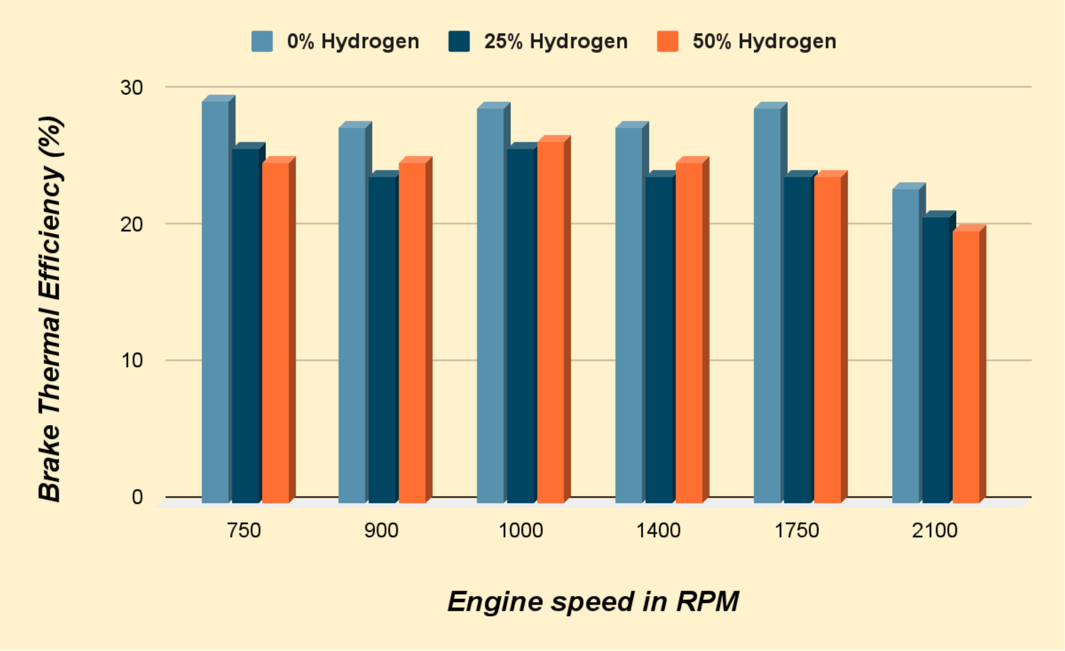


Figure 2 :Brake Thermal Efficiency with different percentages of hydrogen.

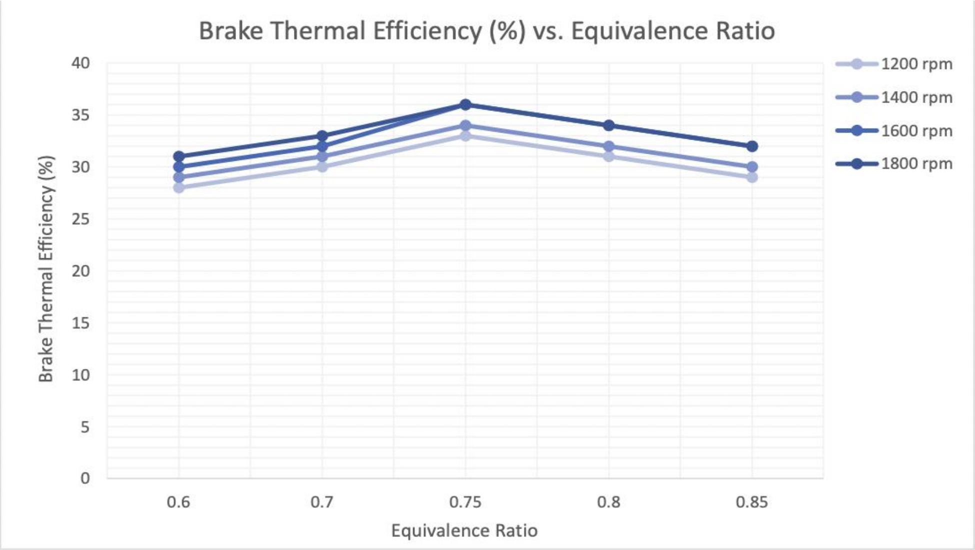


Figure 3: Brake Thermal Efficiency vs. Equivalence ratio

Hydrocarbons emissions

The reason why the flames of hydrogen burn at high speeds and with the largest flammability range in comparison to other fossil fuels is because hydrogen burns at higher rates and consumes more of the fuel than wasted in terms of the amount of hydrocarbons burnt agricultural-wise than any other fuel. It is easier to extinguish the fire from hydrogen as compared to gasoline, which implies that there is no chance of incomplete combustion caused by proximity to the cylinder wall hence reduction in the emissions of hydrocarbons. The issue that comes up when dealing with regular hydrocarbons fuel is during the starting period, commonly referred to as cold start; whereby too many hydrocarbons are not completely burnt hence are emitted. The use of assist fuel cells and hydrogen energy help in solving this issue through the ease of ignition.

Nox Emissions

The other factor that influences NOx emissions is combustion chamber temperature. NOx emissions are produced in peak temperatures within the engines during burning. Lean air/fuel ratios within the engine reduce combustion temperatures and reduce NOx emissions. NOx emissions from dual fuel engines fueled with hydrogen and diesel/gasoline may increase at first because of the higher temperatures caused by hydrogen. Such emissions can be addressed through lean burn processes or exhaust gas recirculation. This lowers combustion chamber temperatures.

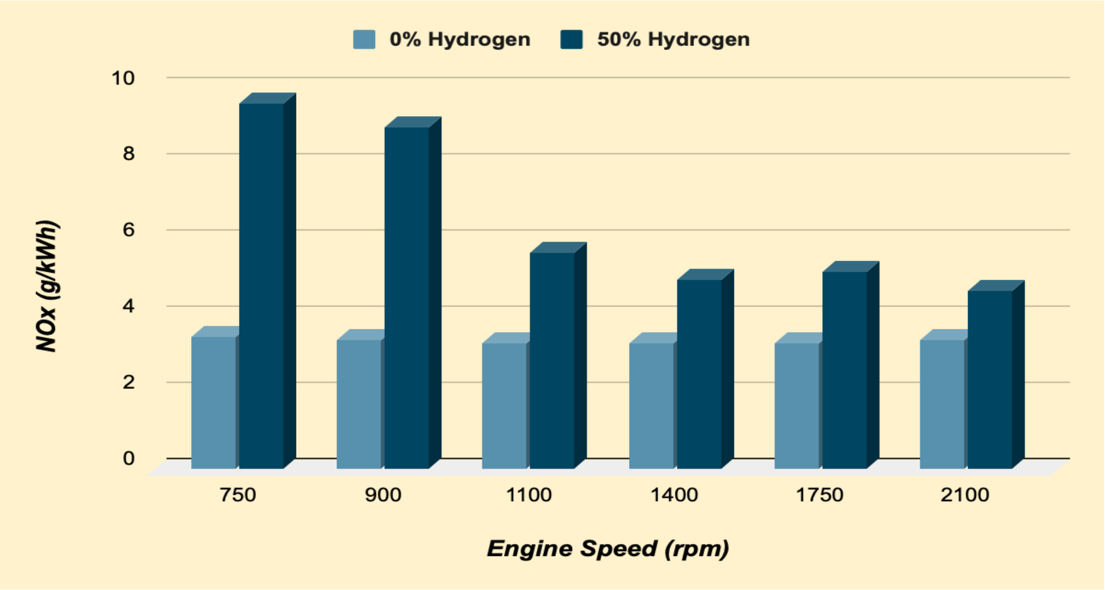


Figure 4: Increased NOx emissions from diesel engines running on hydrogen fuel[1]

III. HYDROGEN PRODUCTION METHODS

There needs to be a process for extracting hydrogen since it does not occur in nature either as an element or a molecule. Although hydrogen might not be in its purest form, there are easy ways of getting hydrogen in the environment. There exists a process that involves extracting hydrogen from those compounds that have hydrogen atoms and separating them from all the other atoms of other elements in the compound.There are several methods for producing hydrogen; namely steam reforming of methane, gasification of biomass, coal, and wastes, thermo-chemical water splitting, and electrolysis. The currently accepted technologies for producing hydrogen are steam methane reforming and coal gasification because of their low costs (<$2/kgH2).

1) Electrolysis

One of the ways of producing carbon-free hydrogen from nuclear energy sources and renewable energy sources involves the splitting of water into oxygen and hydrogen through electrolysis. Therefore, the main purpose of this process is to obtain oxygen and hydrogen through the splitting of water by means of electricity. This process whereby electricity is used to produce hydrogen and oxygen from water is referred to as hydrogen production and it occurs in an electrolyzer. Consequently, the electrolyte used to produce hydrogen and oxygen gas at the cathode and anode, respectively is water. Hydrogen produced from electrolysis possesses a high purity percentage and hence it is very clean. Electrolysis produces green hydrogen, which does not release greenhouse gases, provided renewable energy sources are used such as wind.

2) Natural gas steam reforming

At the current time about 4/5 of hydrogen being generated globally comes from a process known as steam reforming of natural gas (Methane and ethane).The reaction involves interaction between steam and natural gas in the presence of a catalyst and under high temperatures to give hydrogen, carbon monoxide, and small amounts of carbon dioxide.This method is not only economically viable but also environmentally friendly.Its an endothermic reaction which means that it requires some form of heat energy for the reaction to occur.Hydrogen is generated under high pressure about 3 and 25 bars (1 bar =14.5psi) and temperatures ranging between 700-1000C.The reaction can be said to involve

1)Reforming (Steam Methane)
$H_2O+CH_4 \rightarrow CO+3H_2$

2)Shift reaction(Water gas)
$H_2O+CO \rightarrow H_2 +CO_2$

3) Coal gasification

Among all fossil fuels, coal is the one which has the greatest market share and its manufacturing cost is relatively low.

At the initial stage, coal goes through a partial oxidation process to generate carbon dioxide gas, and then oxygen is supplied to the coal to form hydrogen gas. The formation of carbon dioxide gas is the next process after partial oxidation and it acts as a gasifier. Carbon dioxide gas reacts with the carbon generated from coal as a byproduct to form carbon monoxide gas. CO gas when reacted with steam produces hydrogen and carbon dioxide with removal of impurities from gas mixtures. In near future coal gasification can prove to be a more effective method for hydrogen production due to advancement in renewable energy utilization technologies and sufficient coal reserves availability in certain regions despite having insufficient renewable resources. However, it also involves some drawbacks, e.g., it uses a lot of energy.

4) Biomass Gasification

The biomass gasification technique can be applied to generate hydrogen from renewable resources. This process entails the pyrolysis of biomass, which can be agricultural residue or woody biomass, in the presence of steam and oxygen under high temperatures. The combustion of any fossil fuel is not involved in this method. The biomass is introduced into a gasifier and heated to about 700–1200 degrees centigrade using steam or oxygen. The hydrogen content in the synthesized fuel can be further increased through water gas shift reactions, ensuring the highest amount of hydrogen production. However, this is not the case for coal gasification since the process involves organic material, and unlike biomass, the latter gasifies much faster than coal. Moreover, the use of gas turbines allows the burning of biomass synfuel to generate electricity, resulting in higher energy efficiency. The emission of carbon dioxide by biomass is lower due to its intake during the growth phase of its biomass. Therefore, the technique of biomass gasification ensures clean environmental emissions of greenhouse gases.

5) Microbial biomass Conversion

Conversion of Biomass through Microbes is a method where biomass is converted to hydrogen gas and biofuel among others through the help of microorganisms such as fungi, bacteria, and algae.The technique exploits the capacity of microbes to produce hydrogen by ingestion and digestion.Conversion processes use biomass which is renewable hence decreasing reliance on non-renewable sources such as fossil fuels.Anaerobic bacteria digest biomass resulting in hydrogen, carbon dioxide, and organic acids. The process does not require sunlight; it is known as dark fermentation since no light is used.Subsequently, organic acids are converted to hydrogen through light; the process is called photofermentation.

IV. TYPES OF HYDROGEN

Following are the types of hydrogen on the basis of production method and the resulting carbon footprint. While all these types end up as H_2 fuel for engines (Internal Combustion or Fuel Cells), their environmental impact varies wildly.

1. GREEN HYDROGEN

Green Hydrogen is derived from electrolysis, where water is separated by applying an electrical current to water using renewable energy sources such as solar or wind energy. The most significant feature of green hydrogen is that it is completely carbon neutral since no emissions are created when producing it. The most valuable aspect of green hydrogen is its full sustainability, which supports industries to meet their "Net Zero" targets. On the other hand, one of the downsides is that it costs a lot more than conventional processes. Another disadvantage is its high dependence on renewable energy resources. Its application is limited at present to pilot programs involving trucks, public transportation buses, and serving as an energy medium in shipping and airline applications.

2. BLUE HYDROGEN

Blue Hydrogen is extracted from methane gas using steam methane reforming, but with one additional process: carbon capture and storage (CCS). The characteristic feature of Blue Hydrogen is that its carbon intensity is much lower compared to fossil hydrogen because 90–95% of carbon emissions are captured and stored underground. The advantage is that it is cheaper than Green Hydrogen, yet low-carbon, and thus, it is a practical transition fuel. The disadvantages include the high cost of installing and maintaining carbon capture technology and methane leaks that might occur during production. It has broad application in engines and is a suitable fuel for converting gas systems to "decarbonizing" systems.

3. GREY & BROWN HYDROGEN

The two most widespread hydrogen varieties include Grey Hydrogen (natural gas through SMR) and Brown/Black Hydrogen (coal gasification). Their key characteristic is that their carbon footprint is significantly higher compared to other alternatives: on average, 9 to 20 tonnes of CO2 are emitted into the atmosphere for each tonne of hydrogen. However, there are clear advantages to their use: they are inexpensive to generate and use well-established and effective technologies. In turn, the disadvantages can be attributed to the fact that these sources are extremely damaging to the environment and are gradually being replaced by carbon taxes. Today, they account for the majority of the hydrogen market, powering chemical engines, producing ammonia, and oil refining.

4. WHITE HYDROGEN

White Hydrogen refers to natural hydrogen that occurs in the earth beneath the ground. The advantage of this form of hydrogen is that it does not need to be manufactured through any form of industrial process; all it needs is to be extracted. The greatest advantage that this form of hydrogen offers is that if enough deposits are discovered, it can become the cheapest and most environmentally friendly source of hydrogen ever. The disadvantage is that the technology needed for its extraction is unavailable, and it is hard to come by.

5. OTHER SPECIALIZED HYDROGEN

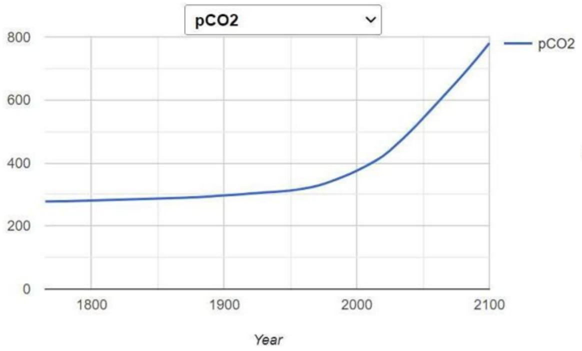
Pink Hydrogen is produced via electrolysis powered by nuclear energy, offering the merit of high-volume, carbon-free production with the demerit of nuclear waste concerns.
Turquoise Hydrogen uses methane pyrolysis to split natural gas into H2 and solid carbon (carbon black), which has the merit of creating no gaseous CO2.
Yellow Hydrogen specifically refers to electrolysis powered by solar energy. Their usage is mostly experimental or site-specific, such as using nuclear-powered Pink Hydrogen to fuel local industrial fleets near power plants.

V. SCENARIO ANALYSIS

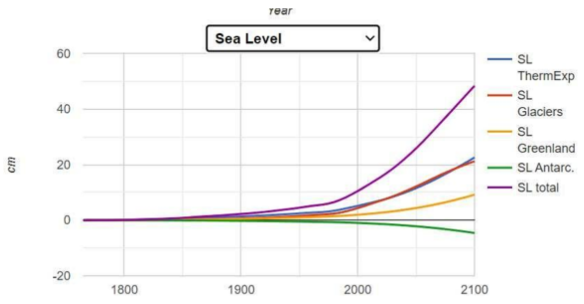
1. A1 Scenario

Fossil Fuel Use - (Input In ISAM)

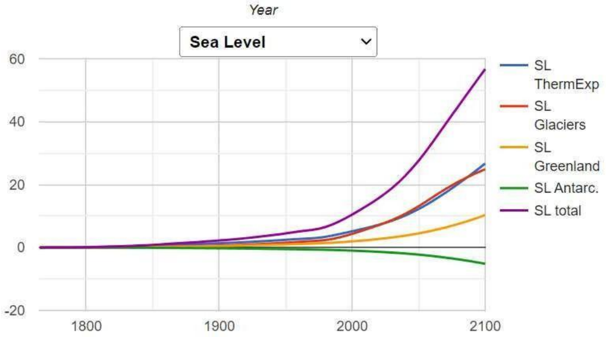
Year	2015	2020	2025	2050	2075	2100
CO_2 From fossil Fuels	11	12	14	25	28	32



(Figure 5: pCO_2 vs Year)



(Figure 6: Temperature rise vs Year)



(Figure 7: Sea level rise vs Year)

Output in year 2100:

a. pCO_2 - 1001 ppm

b. Temperature rise - 3.45 °c

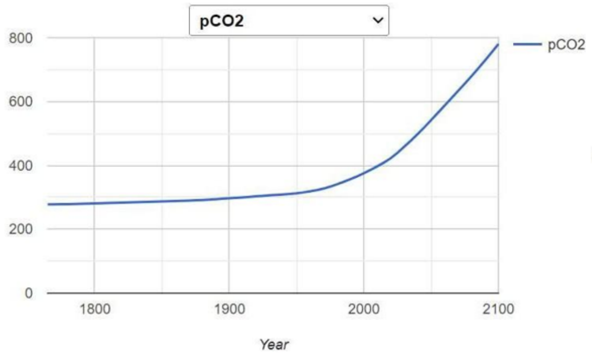
c. Sea level rise - 56.725 cm

If no further efforts are made to curb the CO2 Emissions

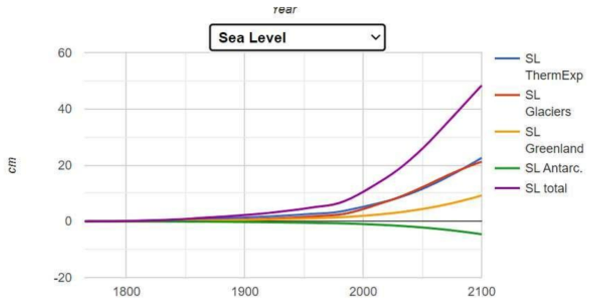
2. **A2 Scenario**

Fossil Fuel Use - (Input in ISAM)

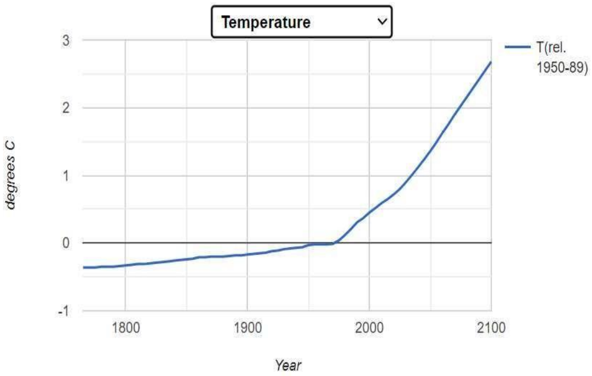
Year	2015	2020	2025	2050	2075	2100
CO_2 From fossil Fuels	9	11	13	17	18	20



(Figure 8 : pCO_2 vs Year)



(Figure 9: Sea level rise vs Year)



(Figure 10: Temperature rise vs Year)

<u>Output in year 2100:</u>

a. pCO_2 - 780 ppm

b. Temperature rise - 2.68 °c

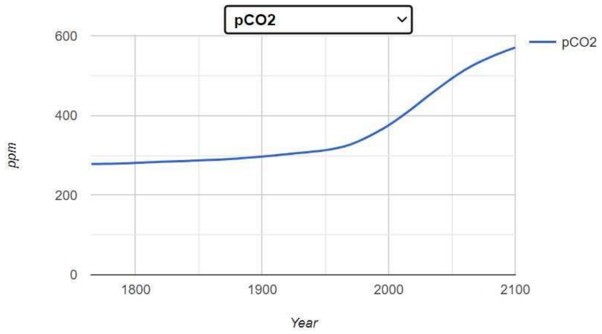
c. Sea level rise - 48.432 cm

If minimum efforts such as energy conservation and using alternative energy systems are put in place.

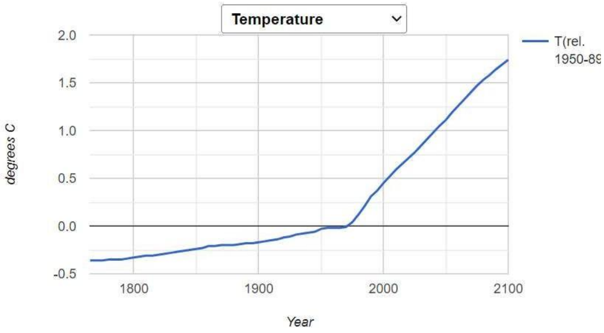
3. B1 Scenario

Fossil Fuel Use (Input in ISAM)

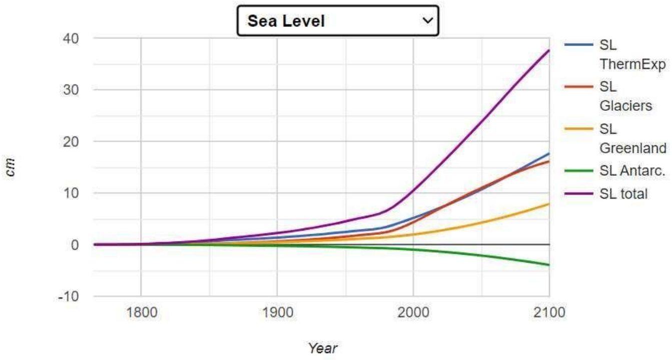
Year	2015	2020	2025	2050	2075	2100
CO_2 From fossil Fuels	9	9.5	10	10	8	7



(Figure 11: pCO_2 vs Year)



(Figure 12: Temperature vs Year)



(Figure 13: Sea level rise vs Year)

<u>Output in year 2100:</u>

a. pCO_2 - 570 ppm

b. Temperature rise - 1.74°c

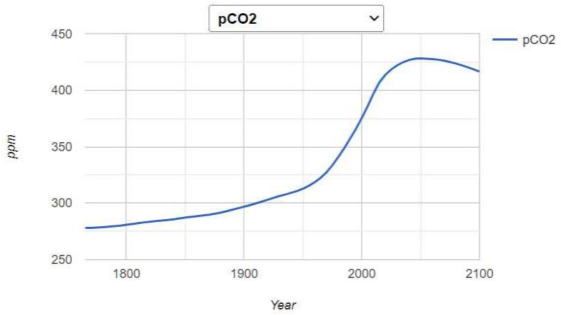
c. Sea level rise - 37.712 cm

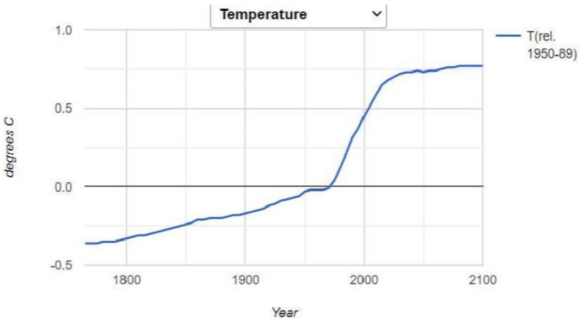
If we are able to replace current energy systems completely with cleaner energy sources

4. B2 Scenario

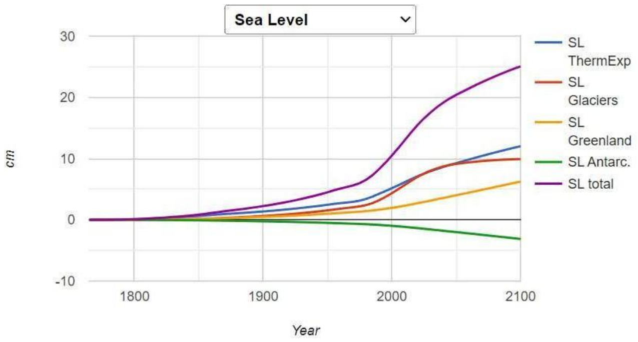
Fossil Fuel Use (Input in ISAM)

Year	2015	2020	2025	2050	2075	2100
CO_2 From fossil Fuels	7.1	6	5.1	2.2	1	0.4





(Figure 14: pCO_2 vs Year) (Figure 15: Temperature vs Year)



(Figure 16: Sea level rise vs Year)

<u>Output in year 2100</u>:

a. pCO_2 - 416 ppm
b. Temperature rise - 0.77°c
c. Sea level rise - 24.674 cm

If we are able to reach our Net zero goals as discussed in the Paris Agreement

We may estimate that in the case of scenario B2 where the nations decide on using hydrogen, both the carbon dioxide emissions and the use of fossil fuels will decrease by 80% until 2050. We may have a fair possibility of reversing or controlling the problem of climate change from causing more damage.
At the moment, the whole world is finding itself trying to look for ways out of the dilemma of fossil fuel use because alternative energies are quite unstable and have their downsides.

CHAPTER 6
INJECTION METHODS

Table 2: Main properties of gaseous hydrogen and gasoline

Parameter	**Gasoline**	**Hydrogen**
Molecular Formula	CnH1.87n	H2
Density (kg/m^3)	4.40	0.084
Boiling point (C) @ 1bar	27-225	-252.9
Lean equivalence ratio	0.6	0.1
Stoichiometric A/F ratio (by mass)	14.8	34.3
Energy content (MJ/Kg)	44	120
Energy content (MJ/L)	32	8
Ignition energy in air (mJ)	0.24	0.02
Ignition Limits in air (Vol%)	1.0-7.6	4.0-75.0
Latent heat of Vaporization (KJ/Kg)	305	461
Flame Temperature in the air (C)	2197	2045
Auto-ignition temp. (K)	550	858
Octane number (RON)	92-98	>=120
Flame speed (m/s)	0.37-0.43	1.85
Quenching distance at stoic. (mm)	2.84	0.64

5.1)Injection Techniques

The choice of injection method for Hydrogen in Internal Combustion Engine (H2ICE) significantly impacts engine performance, efficiency, and emissions, hydrogen can be injected into internal combustion engines, including Fuel Carburetion (FC), Port Fuel Injection (PFI), Direct Injection (DI), Dual- Fuel Injection (DFI), Homogeneous Charge Compression Ignition (HCCI), Stratified Charge Injection (SCI).

1) Fuel Carburetion: One of the simplest and the oldest fuel injection systems; one important advantage with this technique is that it uses lesser pressure than other methods such as the PFI and DI Method. Since most cars have a carburetor engine, it is relatively easy to alter this system to be used in hydrogen engines. Air-Fuel Ratio (AFR) in hydrogen engines is 34.3 while that of gasoline is 14.8 (see Table 2). However, since the AFR ratio is higher in hydrogen engines, there is more chance of Pre-Ignition occurring within the intake manifold. Premature ignition in an open intake manifold causes backfire; the intake valve is open during this process, there is greater chance of the flame being forced back past the intake valve and igniting the combustible material inside the intake manifold. Backfire is particularly a problem with hydrogen engines as a large quantity of the combustible mixture remains in the manifold, it is very important to avoid ignition under these circumstances.

2)Port Fuel Injection System (PFI): The injector is mounted on the side of the intake manifold next to the intake port, and the fuel is directly injected into the air in the intake manifold. The fuel mixes well with air in a relatively uniform fashion. Fuel + air mixture enters the combustion chamber via intake valve. The low ignition energy of hydrogen 0.02mJ and flame quenching distance of 0.64mm, as seen in Table 2, makes the PFI system highly vulnerable to Pre-Ignition, Knocking, and Backfiring. Direct Injection (DI): the injector is mounted directly on the combustion chamber, during the intake stroke, after the air compression process, the injector introduces fuel directly into the combustion chamber. This type of injection method enhances engine performance, increases efficiency, and minimizes emissions, however, it reduces backfire and volumetric efficiency and needs a high pressure injection system of 1500-5000 PSI. At the same time, the direct injection method has a very poor vaporization rate in high rpm conditions, due to the reason that rapid motion of the piston creates less time for air-fuel mixture to be atomized and vaporized properly.

The process of crankcase ventilation is more necessary for hydrogen engines compared to those using gasoline as fuel. This is because the ignition energy required to ignite hydrogen is 0.02mJ while that of gasoline under similar conditions is 0.24mJ (Table 2). This means that hydrogen requires one-twelth of the energy to ignite compared to gasoline, making it relatively easier to ignite. The unburnt hydrogen fuel in the engine cylinders, similar to the case of gasoline engines, tends to escape from the piston rings into the crankcase, and since hydrogen in the crankcase is dry, it ignites easily.

VI. PORT FUEL INJECTION - H2 ICE

7.1) Challenges with PFI-H2 ICE

Usually, the soot particles do not form because there are no carbon-based products of hydrogen combustion, however, the soot particles may be formed due to the lubricating oil combustion or the contaminants present inside the combustion chamber; the presence of soot particles or deposits in the spark plugs acts as the surfaces for heat retention and ignites during the intake stroke causing the backfire phenomenon. As per the experimental studies conducted to enhance the combustion performance of H2ICE, it was observed that higher pressures of hydrogen and high compression result in efficient atomization process and utilization of the EFI system results in precise fuel injection. In their study in 1991-1995, Mathur & Das studied the Time Manifold Injection (TMI) system, which uses the lift-rods driven by camshafts to achieve the proper timing for hydrogen injection using the linkage mechanism. The experimental conditions included MBT, varying compression ratios and engine speed and load. Results indicated that the injection delay had brought about consistent combustion and maximum power, particularly for lean air/fuel ratio. Liu et al., in 2008, carried out a computer-based simulation on the effects of hydrogen injection timings on the intake of hydrogen-air fuel mixture for purposes of avoiding backfire, they used two stages of combustion chamber cooling. The first stage involved exhaust gas recirculation (EGR) where the combustion chamber is cooled through fresh air that passes in it while both the inlet and exhaust valves were opened. The second stage involves the continued cooling of the combustion chamber even when the exhaust valve was closed but fresh air passed into the combustion chamber. In their findings, hydrogen injection only occurs when the temperature in the combustion chamber is less than 858 K (hydrogen auto-ignition temperature as in Table 2). This means that the chamber is cold enough for any form of combustion to occur. Dhyani and Subramanian in 2021- have designed an electronic control mechanism which can be used to avoid backfire by postponing injection timings above 858K (auto-ignition temperature of hydrogen). In order to be able to predict the timing at which the backfire would take place, the tool collected information through different sensors used to monitor exhaust gas temperature, crank angle, and engine oil temperature. In their experiment, they found out that delayed timing in the introduction of hydrogen gave enough time for air to interact with the combustion chamber, thereby cooling the engine.

In regard to hydrogen injection technology improvement, this involves electronic injection systems, precise injection timing control, and effective cooling. During the previous combustion cycle, the presence of left-over exhaust gas raises temperature, thereby increasing the pressure in the combustion chamber. When there is a surplus of heat in the combustion chamber, it causes the fresh hydrogen-air mixture to ignite in the combustion chamber leading to backfire during the intake process. Knocking and backfire are correlated, since intense backfire results from previous knocking cycle that leads to high engine temperature hence backfire. Poor injection timing such as early timing results in an excessively rich fuel-air mixture near the valves. Delays in injection timing result in backfire suppression. Early sparking causes fuel to ignite too soon leading to unstable pressure fluctuations hence backfire. Pre-ignition and incomplete combustion of the previous cycle cause ignition of new fuel in the intake manifold. Significant research efforts have been dedicated to addressing key challenges such as the backfire, pre- ignition, knocking and many more other issues encountered in the use of PFI-H2ICE. Furuhama et al in 1977- Conducted one of the earliest destructive pressure combustion chambers. could reduce the risk of backfire and pre-ignition, and enhance the performance, safety, and efficiency of H2ICE.

7.2) Advantages of using Port Fuel Injection in H2ICE

The PFI permits the introduction of hydrogen directly into the intake manifold, which is easier to implement and modify compared to DI, it also offers sufficient time to form a uniform air-fuel mixture. PFI offers flexibility in optimizing hydrogen injection strategies, such as controlling injection timing. PFI is less complex and cheaper than DI, gaining significant attention of the major automotive and energy industries due to their relatively simple design, affordability, and adaptability. Existing injector could be used for the hydrogen injection with minor changes.

7.3) Emissions

H2ICE emits significantly fewer pollutants compared to conventional gasoline or diesel engines due to the absence of carbon in hydrogen fuel. H2ICE mainly emits Nitrogen Oxides (NOx), and water vapors. NOx formed due the high combustion temperature that enables nitrogen and oxygen from air to combine. Unlike fossil fuel engines, hydrogen combustion does not produce carbon dioxide (CO2) or other hydrocarbons (HC) and particulate matter (PM). NOx emissions in H2ICE are mostly affected by the equivalence ratio, combustion temperature, and air-fuel mixture homogeneity. Lower equivalence ratio (lean conditions) result in lower combustion temperature, which reduces NOx emissions. Higher equivalence ratio (richer mixtures) causes higher in- cylinder temperatures resulting in NOx formation.

In the PFI system, fuel is mixed with air outside the combustion chamber, resulting in more homogenous air-fuel mixtures. This reduces peak temperature during combustion, since NOx formation is highly dependent on the combustion temperature, lower peak temperatures in PFI results in lower NOx emissions. However, due to hydrogen's higher flame speed and lower ignition energy, premixed combustion in PFI can still lead to moderate NOx emissions unless additional strategies, such as exhaust gas recirculation (EGR) or lean-burn conditions, are employed. In the DI system, hydrogen is injected directly into the combustion chamber, which results in high fuel concentration and higher local temperature, and thus higher NOx emissions.

The formation of NOx increases significantly due to localized hotspots where combustion occurs at higher temperatures. Although hydrogen is a clean fuel producing only water upon ideal combustion, these hotspots facilitate the reaction between nitrogen and oxygen from the air, leading to NOx formation. The mitigating technique of ultra lean mixtures or EGR may be required to control emission in DI systems. However, it can compromise power output or efficiency. NOx emission is influenced by the load and injection timings, at low and medium engine loads, delayed injection timing produces a less homogenous mixture

This promotes diffusion combustion, in which the burning process happens unevenly. The presence of the localized high-temperature zones during this type of combustion leads to increased NOx emissions. At high loads, early injection raises NOx levels due to a more favorable global equivalence ratio for NOx formation, this means the overall air-fuel ratio is such that the combustion temperatures are high enough to promote significant NOx formation. As load increases the amount of air required for the combustion also increases, and combustion of excess oxygen and high temperatures results in higher NOx emissions.

VII. RESULTS AND DISCUSSION

8.1) RESULTS

1. Engine Efficiency

Experiments and simulations indicated that hydrogen fuel combustion engines showed better performance in terms of thermodynamic efficiency than conventional petrol engines. Hydrogen combustion allows stable engine work in lean mode due to high flammability range and flame speed, leading to lower fuel consumption and higher thermal efficiency up to 15-25%. Nevertheless, the volumetric engine efficiency was lowered in port fuel injection systems because of the low-density hydrogen, but this problem could be resolved by using direct injection technology.

2. Emission Levels

The first and most important finding was the complete absence of carbon dioxide and CO emission during hydrogen combustion. Only water is left behind after the process; therefore, hydrogen can be considered a zero-carbon fuel. In turn, NO_x emissions were higher at stoichiometric and high loads due to combustion at high temperature levels. The use of lean mode and exhaust gas recirculation successfully reduced NO_x emissions to acceptable levels.

3. Combustion Behavior

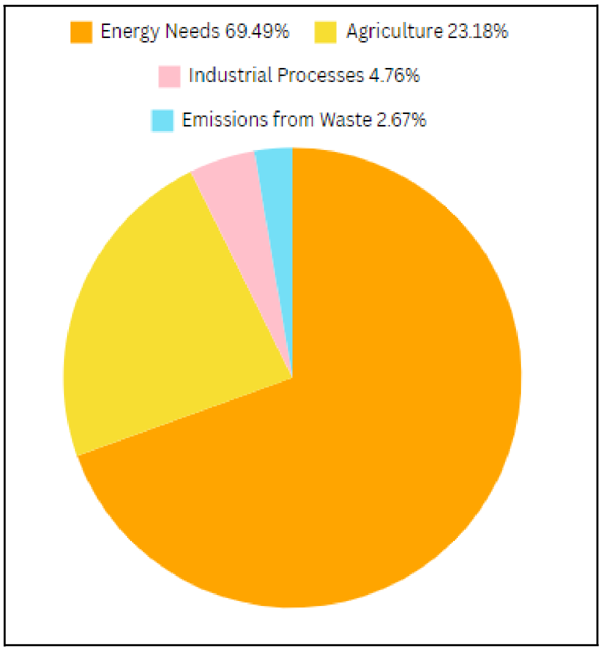
Hydrogen exhibited a faster and more complete combustion process than gasoline, leading to shorter ignition delay and faster pressure rise. This resulted in quicker torque response and stable operation at lean mixtures. Nonetheless, issues such as pre-ignition and backfire were noted, particularly in port-injected configurations

4. Operational Challenges

While hydrogen offers clean combustion, challenges persist in fuel storage, on-board delivery systems, and safety. The high diffusivity and flammability of hydrogen necessitate robust safety mechanisms. Material compatibility and prevention of leakage remain critical areas for future engine design improvements

8.2) CURRENT STATE OF GHG EMISSIONS IN INDIA AND PROPOSED TARGETS.

Based on data provided in 2020 by climatewatchdata.org, we find that India is currently the 3rd largest emitter of GHGs Emitting a total of 3166 Million Tonnes of CO_2 which represents 6.67% of the total emissions after China (at 25.88%) and United states (at 11.13%).



(Figure 17 : Carbon dioxide emission share of India)
Source : climatewatchdata.org
(Does not Include (-1.06%) setoff due to forestry and land use)

Emission per Capita - 2.29 tCO_2
Emission per GDP - 1187.15 tCO_2/M$GDP GDP per Capita - 1933$
(Source : Climatewatchdata.org)

CONCLUSIONS

The elimination of all possible ways of attaining zero emissions would require the process of off-air pollution elimination alongside the production of hydrogen in sustainable ways becoming common practice. In the future, cleaner and better-appearing fuel sources will be required, and hydrogen can be one of them. However, issues like weight, safety, and others ought to be sorted out first before making hydrogen commercially available. Prior to commercialization of hydrogen, there is a need for proper protocols governing its production, distribution, and storage. There will come a time when the earth's generation will require hydrogen as a fuel since it can burn and cook. As a result of the policy change, God gas hydrogen along with infrastructure necessary for the storage of God gas hydrogen which has been a major constraint to hydrogen cars is becoming affordable and realistic. Apart from these comments, hydrogen as a fuel reduces exhaust emission because of subduer air/fuel ratio in hydrogen combustion engines.

Hydrogen electrochemical combustion rather than combustion of hydrogen in hydrogen-based cars in bulldozers will go a long way in reducing CO2 emissions in cities. The current system can be modified to burn hydrogen in SI as well as CI engines with minor modifications in the existing system. With the help of stoichiometric air-fuel mixture, the power generated from hydrogen engines can either be 15% higher or relatively lower than that of gasoline engines. While hydrogen is promising in its ability to serve as a fuel source for internal combustion engines, there is one major limitation associated with hydrogen: NOx emissions from hydrogen engines.

- Apart from making slight changes to the existing systems, hydrogen can be utilized in compression ignition as well as spark ignition engines.
- The lean burn of the combustion of the hydrogen engine as it continues to function could be controlled. It could be feasible to design a syngas engine that will enable effective operations even under high engine speeds and loads.
- In a case where hydrogen is utilized as a combustion fuel in an engine, there will be higher values of H/C ratio and thus low combustion duration leading to high efficiency. Hydrogen, being a clean fuel, will not produce carbon dioxide while in combustion hence producing low amounts of CO2.
- Due to the fast flame speed, less ignition energy required as well as high adiabatic temperature, hydrogen acts as an ideal combustion fuel. This enables more production of heat by the working fluid in the engine as well as high formation of NOx.

- Hydrogen cars have much importance to various individuals. To start with, these are very advanced technologies, which will ensure that the automotive industry operates independently yet demands high quality of hydrogen used.
- In conclusion, overall, hydrogen gas is the most optimal source of energy that can be used in order to reduce or totally stop any emissions produced by automobiles. Nevertheless, hydrogen gas will have to address other issues such as production, transportation, storage, cost, reliability, and safety.

FUTURE SCOPE

9.1) FUTURE SCOPE

1) Engine Design

In future, research could be done in designing IC engines specifically meant for hydrogen-based fuels as opposed to redesigning conventional engines that use fossil fuels like gasoline and diesel.

2) Control of Exhaust Gases

Although there is no production of CO_2 with hydrogen-powered engines, NO_x emission control still poses a problem and must be looked into in future. Catalytic exhaust treatment needs to be optimized in order to cater for future emission limits.

3) Hybrid and Dual Fuel Engines

Using hydrogen-fueled IC engines alongside hybrid engines or dual fuel engines (Hydrogen-natural gas) is one area that needs much research in order to optimize the efficiency of the fuel used in these engines. Intelligent controls and intelligent fueling systems would be essential for this purpose.

4) Infrastructure and Integrations

With the growth of hydrogen-based infrastructures, the practical applications of hydrogen engines would be greatly enhanced. Future research could look into areas such as the life-cycle analysis and cost benefit analyses as well as use of green hydrogen in the engines.

5) Transition Technology

IC engines running on hydrogen fuel could provide a transition from current IC engines technology to fuel cell technologies.

9.2) TECHNOLOGICAL POSSIBILITIES AND PROPOSALS

1) Carbon Capture and Sequestration – CCS is an upcoming technological possibility which suggests that we should trap the CO2 emissions released from their sources and store them beneath the earth surface.

2) Rapid decrease in emission sources – We will have to make rapid changes in our current energy production processes using alternative energy technologies. By the year 2030, we will have to adopt new techniques such as nuclear fusion and nuclear fission.

9.3) MINIMIZING THE GEOGRAPHIC IMPACT OF CLIMATE CHANGE

There are two fundamental concepts that must be adopted to minimize the geographic impact of climate change i.e. Mitigation and Adaptation.

Mitigation Measures-

1)Energy Transition
2)Energy Efficiency
3)Sustainable Practices
4)Technological Advancements

Adaptation Measures -

1)Coastal Protection
2)Smart agricultural practices
3)Early warning and alert systems
4)Urban Planning

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