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# ASSESSMENT OF HYDROGEN AND BIO-FUEL AS SUSTAINABLE ALTERNATIVE FUELS FOR INTERNAL COMBUSTION ENGINES AND THEIR LEGAL STRUCTURE IN NIGERIA

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## ABSTRACT

The growing interest in sustainable alternative fuels for internal combustion engines (ICEs) results from rising concerns over ecological pollution and the depletion of fossil fuel stocks. The study aimed to assess hydrogen and biofuel as sustainable alternative fuels for the internal combustion engine and its legal structure in Nigeria. The study cut across a thorough literature review to compile pertinent information on these alternative fuels' characteristics and manufacturing processes, such as Hydrogen and Acetylene as a sustainable alternative fuel for internal combustion engines, Natural gas as an alternative fuel, and Ethanol as a Fuel for Internal Combustion Engine; Biogas as a sustainable alternative for internal combustion engines. Furthermore, the study discusses the challenges and ways forward for hydrogen, Acetylene, natural gas, Ethanol, and biofuel to be employed as alternative fuels. Also, the study looked into the legal structure of hydrogen and biofuel as alternative fuels for internal combustion engines in Nigeria. The results from the study show that hydrogen and biofuel are suitable replacements for fossil fuels. However, the stakeholders in Nigeria need to develop a robust legal structure for its operations and utilisation in Nigeria. The study concluded by making sustainable suggestions for utilising multi-criteria decision analysis for the stakeholders to successfully develop the legal structure that will also ascertain the quality of alternative fuels produced from hydrogen and biofuel.

**Keywords:** Internal Combustion Engine, Sustainable Alternative Fuels, Energy, Hydrogen and Bio-fuel.

## 1. INTRODUCTION

The history of the internal combustion engine is extensive and goes back many centuries. Early research conducted in the late 17th century by scientists like Huygens and Boyle laid the foundation. Important turning points were reached by Nicéphore Niépce's Pyréolophore in 1807 and Thomas Newcomen's atmospheric steam engine in the early 18th century.[1] Gas engines began to take shape in the middle of the 19th century, with Lenoir's coal gas engine and Otto's four-stroke engine changing the industry. While Daimler built the first motorbike, Karl Benz unveiled the gasoline-powered car in 1885. Internal combustion engines gained a new dimension after diesel created the diesel engine in 1892. The early 20th century saw vehicle commercialisation and mass production, which helped shape the current transportation scene.[2] Automotive propulsion, power generation, and industrial machinery are just a few of the many applications where internal combustion engines (ICEs) are used as the primary power source. The controlled combustion of a fuel-air combination inside of a small space is the basic idea underlying an ICE. This process releases energy that powers mechanical labour. An ICE comprises three parts: an air intake system, a combustion chamber, and an exhaust system.

The air intake system introduces controlled amounts of air that are more accessible, and the combustion chamber mixes them with the proper fuel. The fuel-air mixture ignites, causing a series of quick, regulated combustion events. These events convert chemical energy into thermal energy, resulting in the production of mechanical power. Lastly, the exhaust system makes it possible for the exhaust system also makes it easier to remove combustion byproducts, which promotes effective engine functioning.[3] Energy is essential for advancing humanity, yet the alarming rate at which fossil fuels are used is cause for concern. Due to the population and industrial growth over the past few years, particularly the growth of the automotive industry, there has been

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1 Sadeq, A. M., Homod, R. Z., Hussein, A. K., Togun, H., Mahmoodi, A., Isleem, H. F., ... & Moghaddam, A. H. (2024). Hydrogen energy systems: Technologies, trends, and future prospects. Science of The Total Environment, 173622. https://doi.org/10.1016/j.scitotenv.2024.173622.

2 Sameer, Havilah, P. R., Yadav, U. S., & Sharma, A. K. (2024). Hydrogen Production and Utilisation Through Electrochemical Techniques. In Challenges and Opportunities in Green Hydrogen Production (pp. 177-209). Singapore: Springer Nature Singapore. https://doi.org/10.100 7/978-981-97-1339-4_8.

3 Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2024). Green hydrogen: A pathway to a sustainable energy future. International Journal of Hydrogen Energy, 50, 310-333. https:// doi.org/10.1016/j.ijhydene.2023.08.321.

a significant increase in the demand for fossil fuels.[4] Along with a lack of fuel sources, this affects emissions. additionally, it is believed that the principal cause of the acceleration of global warming (GHG emissions) is internal combustion (IC) engines that run on fossil fuels.[5] People are constantly looking for strategies to stop the global warming caused by greenhouse gases because of the negative repercussions of climate change. Globally accepted statistics show that $CO_2$ gas accounts for an incredible 76% of all greenhouse gases released into the atmosphere.

Many nations are considering banning cars with internal combustion engines to cut greenhouse gas emissions, and they are also putting in place policies that will encourage the use of electric vehicles.[6] Internal combustion engine alternative fuels are now more crucial than ever as the globe struggles to address climate change and environmental sustainability. Researchers and engineers have been investigating various sustainable options in the search for more environmentally friendly transportation solutions.[7] Hydrogen, Acetylene, natural gas, Ethanol, and biofuels are intriguing. These alternative fuels allow moving away from fossil fuels while providing cleaner combustion and lower emissions. This article examines these environmentally friendly options in-depth and considers how they might power internal combustion engines.[8] As a green and sustainable supernumerary for conventional gasoline or diesel, hydrogen fuel has attracted significant attention. Hydrogen generates power in fuel cells while only releasing water vapour as a by-product. As a result, hydrogen-powered vehicles have no emissions and have a high level of energy efficiency. Before widespread

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4 Leach, F., Kalghatgi, G., Stone, R., & Miles, P. (2020). The scope for improving the efficiency and environmental impact of internal combustion engines. Transportation Engineering, 1, 100005. https://doi.org/10.1016/j.treng.2020.100005

5 Kalghatgi, G. T. (2015). Developments in internal combustion engines and implications for combustion science and future transport fuels. Proceedings of the Combustion Institute, 35(1), 101-115. https:// doi.org/10.1016/j.proci.2014.10.002

6 Van Basshuysen, R., & Schäfer, F. (Eds.). (2016). Internal combustion engine handbook. SAE International.

7 Kalghatgi, G. (2018). Is it really the end of internal combustion engines and petroleum in transport?. Applied Energy, 225, 965-974. https://doi.org/10.1016/j.apenergy.2018.05.076

8 Qian, Y., Sun, S., Ju, D., Shan, X., & Lu, X. (2017). Review of the state-of-the-art of biogas combustion mechanisms and applications in internal combustion engines. Renewable and Sustainable Energy Reviews, 69, 50-58. https://doi.org/10.1016/j.rser.2016.11.059

acceptance can happen, however, issues, including infrastructure for the production, storage, and delivery of hydrogen, must be resolved.[9]

This paper will thoroughly assess hydrogen and bio-fuel as sustainable alternative fuels for the internal combustion engine and their legal structure in Nigeria. Seeking to grasp hydrogen, Acetylene, natural gas, Ethanol, and biofuels' applicability in the transportation sector by comparing previous studies and studying their benefits, drawbacks, and sustainability aspects. Also, developing a dynamic legal structure will enable the transportation industry to do quality checks on the produced products and with quality operations.

## 2. HYDROGEN AS SUSTAINABLE ALTERNATIVE FUEL FOR INTERNAL COMBUSTION ENGINE

According to Yang et al.[10] the history of hydrogen in internal combustion engines (ICE) spans several centuries and is characterised by ongoing breakthroughs and difficulties. The hunt for other fuels for internal combustion engines began in the 19th century with the work of innovators and researchers. Hydrogen, the lightest element among the various options, was an intriguing choice. By building the first internal combustion engine powered by hydrogen in 1807, Swiss inventor François Isaac de Rivaz made an essential advancement and laid the groundwork for hydrogen's link with ICE technology. Aghaali et al.[11] observed that the experimental phase persisted as the 19th century gave way to the 20th, with hydrogen becoming more popular as a spark-ignition fuel for internal combustion engines. The high-octane rating and quick ignition of hydrogen intrigued scientists and engineers. It was an enticing option for combustion engines due to these qualities. However, its widespread adoption was hampered by severe

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9 Verhelst, Sebastian, James WG Turner, Louis Sileghem, and Jeroen Vancoillie. "Methanol as a fuel for internal combustion engines." Progress in Energy and Combustion Science 70 (2019): 43-88. https://doi.org/10.1016/j.pecs.2018.10.001

10 Yang, Z., Konovalov, D., Radchenko, M., Radchenko, R., Kobalava, H., Radchenko, A., & Kornienko, V. (2022). Analysis of efficiency of thermopressor application for internal combustion engine. Energies, 15(6), 2250. https://doi.org/10.3390/en15062250

11 Aghaali, H., & Ångström, H. E. (2015). A review of turbocompounding as a waste heat recovery system for internal combustion engines. Renewable and sustainable energy reviews, 49, 813-824. https://d oi.org/10.1016/j.rser.2015.04.144

obstacles like hydrogen storage and distribution. Zhu et al.[12] proposed that hydrogen usage in ICE changed in the middle of the 20th century. Researchers investigated hydrogen's potential as a blending agent rather than using it as the primary fuel. In a process known as hydrogen enrichment, small amounts of hydrogen can be added to the fuel mixture to increase combustion efficiency and lower emissions. This ground-breaking method paved the way for future developments in the use of hydrogen in internal combustion engines.

Reitz and Duraisamy.[13] In contrast to gasoline engines, which rely on spark ignition, hydrogen engines frequently use compression ignition, and the proper air-to-fuel ratio must be attained for effective combustion and maximum power. Due to the high temperatures produced during combustion, hydrogen engines require robust cooling systems. Furthermore, since hydrogen is less lubricious than gasoline, it is crucial to use the proper lubricant. Specialised oils are employed to ensure smooth functioning and reduce wear and tear.

Aliramezani et al.[14] thought that when compared to other fuels, hydrogen has a wide range of flammability, which enables it to be used in an internal combustion engine utilising a variety of fuel-air combinations. This is a critical benefit, as hydrogen can function effectively in a lean mixture. When operating on a slim variety, a car often has a better fuel economy and more complete combustion. Compared to gasoline, hydrogen has deficient ignition energy and takes around ten times less energy to ignite. Because of this property, hydrogen engines can reliably and quickly ignite lean mixtures, according to Bates & Dolle.[15] Several difficulties must be overcome to assess

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12 Zhu, S., Hu, B., Akehurst, S., Copeland, C., Lewis, A., Yuan, H., ... & Branney, C. (2019). A review of water injection applied on the internal combustion engine. Energy conversion and management, 184, 139-158. https://doi.org/10.1016/j.enconman.2019.01.042

13 Reitz, R. D., & Duraisamy, G. (2015). Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines. Progress in Energy and Combustion Science, 46, 12-71. https://doi.org/10.1016/j.pecs.2014.05.003

14 Aliramezani, M., Koch, C. R., & Shahbakhti, M. (2022). Modelling, diagnostics, optimisation, and control of internal combustion engines via modern machine learning techniques: A review and future directions. Progress in Energy and Combustion Science, 88, 100967. https:// doi.org/10.1016/j.pecs.2021.100967

15 Bates, R., & Dölle, K. (2017). Syngas use in internal combustion engines review. Advances in Research, 10(1), 1-8. https://doi.org/10.9734/AIR/ 2017/32896

hydrogen performance in ICEs. Fuel transportation and storage is an important consideration. Due to its low volumetric density, hydrogen is difficult to store and deliver securely. Therefore, to meet this issue, it is crucial to develop lightweight, portable, and dependable storage technologies, including high-pressure tanks or cutting-edge materials like solid-state hydrogen storage. The regulation of emissions is another area of emphasis. Although burning hydrogen produces little direct emissions, nitrogen oxides (NOx) can develop at high combustion temperatures.[16] Advanced combustion control techniques, exhaust gas recirculation, and catalytic after-treatment systems are required to reduce NOx emissions and meet strict emission criteria.

Jia et al.[17] explained that in the second half of the 20th century and beyond, genuine innovations in the use of hydrogen in ICE were realised. As worries about sustainability and the environment rose, hydrogen became a clean and sustainable energy source. As research efforts increased, significant progress was achieved in tackling the problems related to hydrogen storage, distribution, and combustion.[18] Figure 1 illustrates the analysis of developed hydrogen for ICEs, showing the precombustion chamber and the implementation of low-pressure pumps and the heat exchanger process. According to Kumar et al.,[19] hydrogen-driven internal combustion engines are presently being developed as gas, a promising approach to decarbonising transportation. Hydrogen is the only fuel used in these engines, taking advantage of their effective combustion and low emissions. Another emerging technology paving the way for a new generation of emission-free automobiles is hydrogen fuel cell technology, which uses hydrogen to create electricity to

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16 Zhen, X., & Wang, Y. (2015). An overview of methanol as an internal combustion engine fuel. Renewable and Sustainable Energy Reviews, 52, 477-493. https://doi.org/10.1016/j.rser.2015.07.083

17 Jia, M., Gingrich, E., Wang, H., Li, Y., Ghandhi, J. B., & Reitz, R. D. (2016). Effect of combustion regime on in-cylinder heat transfer in internal combustion engines. International Journal of Engine Research, 17(3), 331-346. https://doi.org/10.1177/1468087415575647

18 Zhang, L., Jia, C., Bai, F., Wang, W., An, S., Zhao, K., ... & Sun, H. (2024). A comprehensive review of the promising clean energy carrier: Hydrogen production, transportation, storage, and utilisation (HPTSU) technolo gies. Fuel, 355, 129455. https://doi.org/10.1016/j.fuel.2023.1294 55.

19 Kumar, V., Gupta, D., & Kumar, N. (2015). Hydrogen use in internal combustion engine: A review. International Journal of Advanced Culture Technology, 3(2), 87-99.

power electric motors. In the ongoing search for greener, more sustainable energy sources, hydrogen has shown promise.

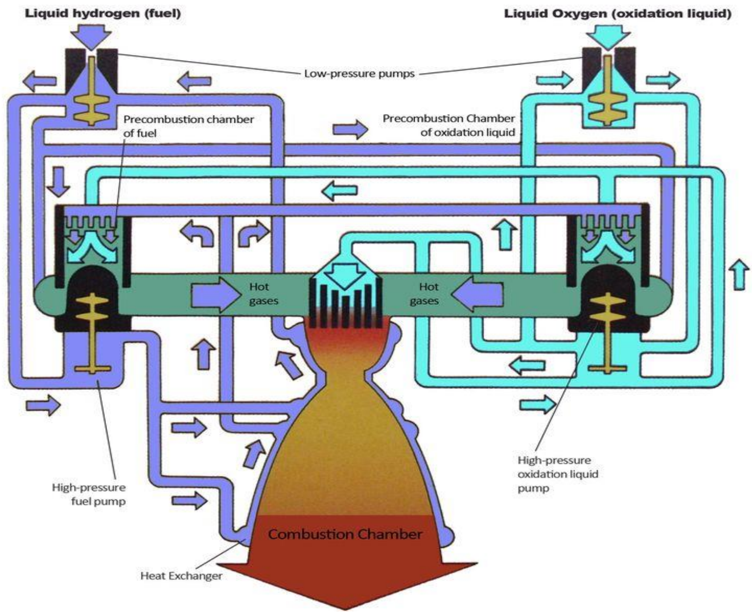


Figure 1: Diagram of Hydrogen Internal Combustion Engine[20]

Shind & Karunamurthy[21] then discussed that although hydrogen fuel cells have received attention, the hydrogen internal combustion engine (ICE) presents a practical option for the transportation industry. Learning about hydrogen engines and understanding the foundations of hydrogen as a fuel source is critical. The most prevalent element in the universe, hydrogen, can be produced electrochemically by electrolysing water, using natural gas, or gasifying biomass. Hydrogen combines with oxygen during combustion, but water vapour and heat are the only by-products. As a result, hydrogen is a clean and eco-friendly energy source. The main parts of a hydrogen engine

[20] Ibid

[21] Shinde, B. J., & Karunamurthy, K. (2022). Recent progress in hydrogen-fuelled internal combustion engine (H2ICE)–A comprehensive outlook. Materials Today: Proceedings, 51, 1568-1579. https://doi.org/10.1016/j. matpr.2021.10.378

are comparable to those of a conventional internal combustion engine. According to Koten[22] some examples are the cylinder block, pistons, connecting rods, crankshaft, valves, fuel injectors, and spark plugs. However, several adjustments are required to account for hydrogen's unique properties. The hydrogen injection system, which supplies hydrogen to the combustion chamber, is one of the significant changes. Manifold injection and direct injection are the two main techniques. The intake manifold receives hydrogen from the various injection systems, which mixes it with the incoming air. The direct injection technology, in contrast, supplies hydrogen straight into the combustion chamber. Each approach has benefits and drawbacks. The comparative analysis of hydrogen with petroleum products is debited in Table 1.

**Table 1: Comparison between Hydrogen ICE and Petroleum ICE**

| Aspect | Hydrogen ICE | Petrol ICE |
|---|---|---|
| Power output | Comparable | Comparable |
| Efficiency | Higher | Standard |
| Emission | No $C0_2$ Emission | $CO_2$ and Pollutant |
| Fuel availability | Developing | Established |
| Energy density and range | Lower | Higher |
| Vehicle performance | Competitive | Traditionally Superior |
| Reliability | Developing | Established |
| Affordability | Developing | Established |

**Source:** Koten [23]

In line with Comotti & Frigo,[24] Hydrogen in ICEs has several drawbacks and difficulties. Its poor energy density per volume is one of the disadvantages. Since hydrogen has a lower energy density than liquid fuels, larger storage devices are needed to give cars the same range as conventional ones. The entire weight, packing, and design of hydrogen-powered vehicles may be affected by this, necessitating improvements in fuel delivery and storage technologies to ensure practical space usage and preserve vehicle performance. Table 2 presents some selected literature on the sustainability of hydrogen as a quality substitute for petroleum.

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[22] Koten, H. (2018). Hydrogen effects on the diesel engine performance and emissions. International journal of hydrogen energy, 43(22), 10511-10519. https://doi.org/10.1016/j.ijhydene.2018.04.146

[23] Ibid Koten

[24] Tsujimura, T., & Suzuki, Y. (2017). The utilisation of hydrogen in hydrogen/diesel dual fuel engine. International journal of hydrogen energy, 42(19), 14019-14029. https://doi.org/10.1016/j.ijhydene.2017 .01.152

Table 2: Hydrogen as a Sustainable Alternative Fuel for Internal Combustion Engines

| **Author Details** | **Engine Type and Simulation Mode** | **Method of Preparation** | **Finding** |
|---|---|---|---|
| Comotti et al.[25] | Internal Combustion Engine for vehicular prototype | This study uses the Ammonia decomposition method for the hydrogen generation process | The efficiency of the hydrogen generation process using ammonia may not be optimal, leading to a lower overall energy conversion efficiency. |
| Işık et al.[26] | Internal combustion Engine | The study shows that the Biomass gasification (BG) method is one of the sustainable ways of producing hydrogen energy. | The finding shows that various methods have been used for hydrogen generation, and the biomass gasification method produces excellent hydrogen. |
| Erden and Karakilcik.[27] | Chlor-alkali reactor | The hydrogen was produced using the electrochemical process where the chlorine, caustic soda, and hydrogen are generated by the electrolysis process with the help of | The results show that the three salts employed produce hydrogen. However, the KCL has the highest hydrogen production with 437.72 mL/h compared to the |

[25] Comotti, M., & Frigo, S. (2015). Hydrogen generation system for ammonia–hydrogen fuelled internal combustion engines. International Journal of Hydrogen Energy, 40(33), 10673-10686. https://doi.org/ 10.1016/j.ijhydene.2015.06.080.

[26] Işık, G., Parlak, İ. E., & Yıldız, A. (2024). Determination of the best hydrogen production method in Türkiye by using neutrosophic picture fuzzy TOPSIS. Environment, Development and Sustainability, 26(7), 18929-18955. https://doi.org/10.1007/s10668-023-03792-y.

[27] Erden, M., & Karakilcik, M. (2024). Experimental investigation of hydrogen production performance of various salts with a chlor-alkali method. International Journal of Hydrogen Energy, 52, 546-560. https://doi.org/10.1016/j.ijhydene.2023.08.049

| | | | |
|---|---|---|---|
| | | a Chloralkali membrane cell. | $CaCl_2$ and the NaCl. |
| Seddiek et al.[28] | The hydrogen-fuelled internal combustion engines for Marine applications with a case study | This study compared hydrogen production through biomass, pyrolysis, thermochemical water splitting, aqueous phase reforming, water electrolysis, and photoelectrolysis. | The authors present insights into the performance characteristics of hydrogen-fueled marine engines, including power output, efficiency, and emissions. |
| Park et al.[29] | hydrogen-fueled internal combustion engine | The authors employed experimental methods to analyse and quantify the occurrence of backfires under different engine speed conditions and variations among individual engine cylinders. | This work provides significant findings regarding the effect of engine speed and cylinder-to-cylinder variations on backfire in a hydrogen-fueled internal combustion engine. |
| Hamada et al.[30] | in-cylinder flow characteristics of hydrogen-fuelled | The researchers employed computational fluid dynamics (CFD) simulations to model and simulate the flow | Based on their numerical investigation, this work provides significant findings regarding the in-cylinder flow |

28 Seddiek, I. S., Elgohary, M. M., & Ammar, N. R. (2015). The hydrogen-fuelled internal combustion engines for marine applications with a case study. Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike, 66(1), 23-38. https://hrcak.srce.hr/136844

29 Park, C., Kim, Y., Choi, Y., Lee, J., & Lim, B. (2019). The effect of engine speed and cylinder-to-cylinder variations on backfire in a hydro gen-fueled internal combustion engine. International Journal of Hydro gen Energy, 44(39), 22223-22230. https://doi.org/10.1016/j.ijhydene. 2019.06.058

30 Hamada, K. I., Rahman, M. M., Ramasamy, D., Noor, M. M., & Kadirgama, K. (2016). Numerical investigation of in-cylinder flow characteristics of hydrogen-fuelled internal combustion engine. Journal of Mechanical Engineering and Sciences, 10(1), 1792-1802. https://doi. org/10.15282/jmes.10.1.2016.4.0172

| | | | |
|---|---|---|---|
| | internal combustion engine | behaviour within the engine cylinder. | characteristics of a hydrogen-fueled internal combustion engine. |
| Akal et al.[31] | Hydrogen usage in internal combustion engines (gasoline-LPG-diesel) | The usage of hydrogen in internal combustion engines (gasoline-LPG-diesel) from the perspective of combustion performance. | This work discusses the effects of hydrogen on various combustion parameters, including combustion stability, engine efficiency, emissions (such as NOx and $CO_2$), and knock resistance. |
| Chaudhary et al.[32] | fuel cell app fuel cell applications | Hydrogen was produced by steam reforming of methane and methanol, aluminium-assisted hydrolysis, and various electrolysis techniques for water. | The study concluded that this was derived from their possible energy-economic significance. The feasibility of various hydrogen generation techniques is also mentioned, especially in fuel cell applications. |
| Luo et al.[33] | NOx emission of a turbocharge | These authors provide direct insights into the combustion characteristics of | Although the study investigates NOx emissions from the turbocharged hydrogen |

[31] Akal, D., Öztuna, S., & Büyükakın, M. K. (2020). A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect. International journal of hydrogen energy, 45(60), 35257-35268. https://doi.org/10.1016/j.ijhydene.2020. 02.001.

[32] Chaudhary, K., Bhardvaj, K., & Chaudhary, A. (2024). A qualitative assessment of hydrogen generation techniques for fuel cell applications. Fuel, 358, 130090. https://doi.org/10.1016/j.fuel.2023.1300 90.

[33] Luo, Q. H., Hu, J. B., Sun, B. G., Liu, F. S., Wang, X., Li, C., & Bao, L. Z. (2019). Experimental investigation of combustion characteristics and NOx emission of a turbocharged hydrogen internal combustion engine. International journal of hydrogen energy, 44(11), 5573-5584. https://doi.org/10.1016/j.ijhydene.2018. 08.184

| | | | |
|---|---|---|---|
| | d hydrogen internal combustion engine | hydrogen engines, including parameters such as ignition timing, combustion duration, and peak pressure. | internal combustion engine, there could be gaps in optimisation strategies to reduce these emissions further. |
| Welch et al.[34] | Hydrogen Direct Injection Technology for Internal Combustio n Engines | The authors diligently employ a systematic approach to investigate and evaluate the challenges of developing hydrogen direct injection technology for internal combustion engines. | The paper shed crucial insights into fuel storage and supply, combustion characteristics, engine modifications, and compatibility concerns. |
| Hamzeh loo et al.[35] | Hydrogen Direct Injection for Internal Combustio n Engines | The researchers created a computational engine model, considering essential aspects like injector setup, combustion chamber shape, and surrounding conditions. | The findings and gaps identified in the research paper encompass significant outcomes and areas for further investigation regarding hydrogen direct injection in internal combustion engines. |

[34] Welch, A., Mumford, D., Munshi, S., Holbery, J., Boyer, B., Younkins, M., & Jung, H. (2008). Challenges in developing hydrogen direct injection technology for internal combustion engines (No. 2008-01-2379). SAE Technical Paper. https://doi.org/10.4271/2008-01-2379

[35] Hamzehloo, A., & Aleiferis, P. (2013). Computational study of hydrogen direct injection for internal combustion engines (No. 2013-01-2524). SAE Technical Paper. https://doi.org/10.4271/2013-01-2524

| | | | |
|---|---|---|---|
| Onorati et al.[36] | Hydrogen for future internal combustion engines | Precise injection timing control is necessary to prevent backfire and surface ignition, requiring careful adjustment. | Hydrogen's numerous physical, chemical, and thermal properties render it superior to conventional fuels. However, these properties also pose practical challenges in its application. |

Source: Author work Literature Analysis

Figure 2 illustrates several ways in which hydrogen is produced. The foundation of chemical heat reforming is the catalysis of methane (usually at temperatures above 800 C) with steam to produce hydrogen and carbon dioxide.[37] The water-gas change process is then triggered by the generated CO interacting with the water vapour to produce $H_2$ and $CO_2$. Improved alkaline upgrades, partial oxidation, steam reforming, and thermal cracking modification are some hydrocarbon-based processes for producing hydrogen.

36 Onorati, A., Payri, R., Vaglieco, B. M., Agarwal, A. K., Bae, C., Bruneaux, G., ... & Zhao, H. (2022). The role of hydrogen for future internal combustion engines. International Journal of Engine Research, 23(4), 529-540. https://doi.org/10.1177/14680874221081947

37 Qazi, U. Y. (2022). Future of hydrogen as an alternative fuel for next-generation industrial applications; challenges and expected opportunities. Energies, 15(13), 4741. https://doi.org/10.3390/en1513 4741.

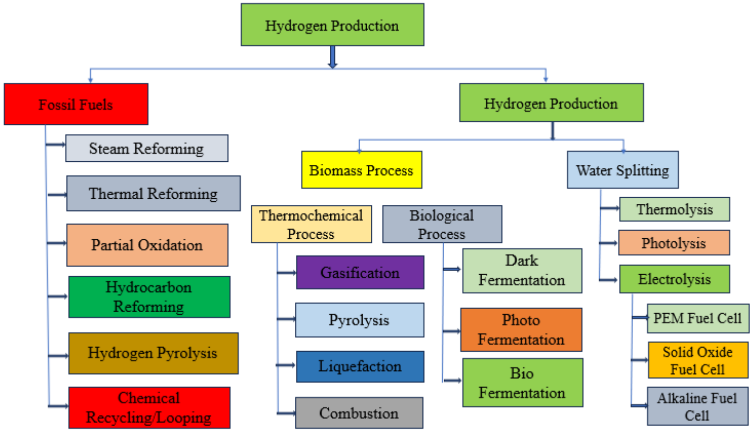


Figure 2. Hydrogen Production Technology
Source: Qazi[38]

## 3. ACETYLENE AS A FUEL FOR INTERNAL COMBUSTION ENGINE

After being heated in an electric furnace with coke and calcium oxide to create calcium carbide, the calcium carbide is then hydrolysed to form Acetylene. Acetylene can be utilised as an alternative fuel in IC engines since it is a colourless gas that is highly flammable and rapidly releases energy. Dimitriou & Tsujimura.[39] according to history, Edmund Davy, the younger sibling of renowned chemist Humphry Davy, is credited with discovering Acetylene. The study initially observed a gas created by heating a solution of calcium carbide and water in 1836. However, as shown in Figure 3, Acetylene was employed as a fuel source in the late 19th century. Georges Claude, a French engineer, created a commercial method to produce Acetylene in 1892 by electrically irradiating calcium carbide. The extensive use of Acetylene for heating and lighting resulted from this discovery.

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38 ibid

39 Dimitriou, P., & Tsujimura, T. (2017). A review of hydrogen as a compression ignition engine fuel. International Journal of Hydrogen Energy, 42(38), 24470-24486. https://doi.org/10.1016/j.ijhydene.2017.07. 232

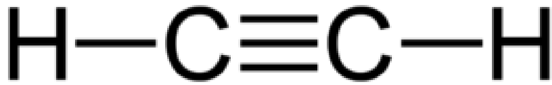

Figure 3 Diagram of the Hydrocarbon Component of Acetylene
Source: Singh et al.[40]

The search for sustainable energy sources has gained importance recently, according to Ilhak et al.[41] Researchers and engineers have been looking at alternative fuels that could replace conventional fossil fuels as concerns about climate change and air pollution continue to rise. Acetylene, a highly flammable gas with potential for usage in internal combustion engines, is one such fuel that has attracted interest. Nikitin & Mikhalchenko[42] thought that Engineers began investigating Acetylene as a fuel for internal combustion engines as the use of automobiles increased in the early 20th century. In actuality, the Belgian engineer Jean Joseph Étienne Lenoir created the first automobile that ran exclusively on Acetylene in 1860. Lenoir's car had a straightforward single-cylinder engine, and even though it was not as efficient as current engines, it showed the fuel's promise.

Ilhak et al.[43] propose that the high energy density of Acetylene as a fuel is one of its main benefits. Acetylene is a desirable option for internal combustion engines since it has around 25% more energy per unit volume than gasoline. In addition, Acetylene burns more efficiently and emits fewer greenhouse gases than conventional fuels. Its combustion mechanism produces carbon dioxide and water vapour but no appreciable amounts of

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40 Singh, G., Sharma, S., Singh, J., Kumar, S., Singh, Y., Ahmadi, M. H., & Issakhov, A. (2021). Optimisation of performance, combustion and emission characteristics of acetylene aspirated diesel engine with oxygenated fuels: An Experimental approach. Energy Reports, 7, 1857-1874. https://doi.org/10.1016/j.egyr.2021.03.022

41 İlhak, M. İ., Akansu, S. O., Kahraman, N., & Ünalan, S. (2018). Experimental study on an SI engine fuelled by gasoline/acetylene mixtures. Energy, 151, 707-714. https://doi.org/10.1016/j.energy. 2018.03.108

42 Nikitin, V. F., & Mikhalchenko, E. V. (2022). Safety of a rotating detonation engine fed by Acetylene–oxygen mixture launching stage. Acta Astronautica, 194, 496-503. https://doi.org/10.1016/j.actaastro. 2021.11.035

43 İlhak, M. İ., Doğan, R., Akansu, S. O., & Kahraman, N. (2020). Experimental study on an SI engine fueled by gasoline, Ethanol and Acetylene at partial loads. Fuel, 261, 116148. https://doi.org/ 10.1016/j.fuel.2019.116148

nitrogen oxides or sulfur dioxide. Raman & Kumar[44] explained that several parameters are considered while comparing Acetylene's performance as an alternative fuel to an internal combustion engine. Key performance factors include energy density, combustion characteristics, efficiency, and emissions. Compared to gasoline, Acetylene has a higher energy density or more energy per unit of volume. The power output of acetylene-powered engines may rise due to this higher energy density. Remembering that energy density does not define an engine's total performance by itself is crucial.

Additionally, essential elements like combustion effectiveness and engine design must be considered. Chondhary et al.[45] stated that Acetylene has different combustion properties than gasoline. Acetylene burns at a relatively low ignition temperature and produces a fast flame. These characteristics enhance combustion efficiency and hasten flame spread in acetylene-powered engines. In contrast to gasoline engines, Acetylene may result in more thorough combustion and improved thermal efficiency. Leach et al.[46] believed that the higher energy density of Acetylene and its advantageous combustion properties could improve an engine's overall efficiency. Acetylene-powered engines can provide more helpful work from each unit of fuel consumed thanks to enhanced combustion efficiency. This improved fuel economy can lower fuel prices and operating expenses related to power generation or transportation due to greater efficiency. Reducing emissions and environmental impacts is one of the main reasons for investigating alternative fuels. When Acetylene is burnt in an engine, it emits less carbon dioxide and other greenhouse gases than gasoline. Sulfur dioxide and nitrogen oxides, typical pollutants from petrol engines, are not produced in considerable quantities during the combustion of Acetylene; instead, carbon dioxide and water vapour are the principal products.

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[44] Raman, R., & Kumar, N. (2019). The utilisation of n-butanol/diesel blends in Acetylene Dual Fuel Engine. Energy Reports, 5, 1030-1040. https://doi.org/10.1016/j.egyr.2019.08.005

[45] Choudhary, K. D., Nayyar, A., & Dasgupta, M. S. (2018). Effect of compression ratio on combustion and emission characteristics of CI Engine operated with Acetylene in conjunction with diesel fuel. Fuel, 214, 489-496. https://doi.org/10.1016/j.fuel.2017.11.051

[46] Leach, F., Kalghatgi, G., Stone, R., & Miles, P. (2020). The scope for improving the efficiency and environmental impact of internal combustion engines. Transportation Engineering, 1, 100005. https://doi.org/10.1016/j.treng.2020.100005

Fil et al.[47] ascertained that it is important to remember that the manufacturing and storage of Acetylene may impact the environment. Typically, acetylene production includes calcium carbide's energy-intensive and potentially carbon-emitting reaction with water. Additionally, acetylene gas must be handled and stored safely because of its extreme flammability. Even though Acetylene has promising energy density, combustion properties, efficiency, and reduced emissions, it is vital to consider the entire fuel cycle and related environmental effects. Engine design, optimisation, and safety considerations, among other things, can affect how well acetylene-powered engines work. Further research must be conducted to address issues, improve engine technologies, and ensure safety. The study revealed that varying the compression ratio significantly influenced the engine's performance, emission levels, and combustion characteristics.[48] It was observed that increasing the compression ratio led to improved engine efficiency and lower fuel consumption. However, higher compression ratios also increased nitrogen oxide (NOx) emissions. The study highlighted the trade-off between improved efficiency and increased emissions with different compression ratios.[49]

## 4. NATURAL GAS AS A FUEL FOR INTERNAL COMBUSTION ENGINE

A mixture of gases that includes many hydrocarbons is called natural gas. In the natural world, gases such as carbon dioxide, nitrogen, and methane

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47 Fil, H. E., Akansu, S. O., & Ilhak, M. I. (2022). Experimental assessment on performance, emission and combustion characteristics of the use of diesel-acetylene mixtures at different loads in a ci engine. Fuel, 324, 124469. https://doi.org/10.1016/j.fuel.2022.124469

48 Soni, A.K., Sharma, S.L., D. et al. Effect of compression ratio on performance, emission and combustion characteristics of diesel–acetylene-fuelled single-cylinder stationary CI engine. Clean Techn Environ Policy 19, 1361–1372 (2017). https://doi.org/10.1007/s10098-017-1334-0

49 Sharma, S., Sharma, D., Soni, S. L., & Singh, D. (2022). Experimental investigation on spark-ignition (SI) engine fuelled with Acetylene in dual-fuel mode. Interna tional Journal of Ambient Energy, 43(1), 2369-2375. https://doi.org/10. 1080/01430750.2020.1735519

exist.[50] The earth's natural gas deposits are buried deep beneath other liquid and solid hydrocarbon beds, such as crude oil and coal. Fuel costs are lower for owners of CNG vehicles since compressed natural gas (CNG) is frequently less expensive than gasoline. Extended engine life: CNG burns cleaner than gasoline, so CNG vehicles live longer than petrol vehicles.[51] Lower CNG price: CNG is less expensive than gasoline. Consequently, the overall cost of ownership is reduced. Thodda et al.[52] discussed that natural gas has a protracted and fascinating history that dates back thousands of years. Natural gas has played a vital role in the development of humanity, from its use and discovery by ancient civilisations to its essential function in the creation of energy today. Let's travel back in time to explore this energy resource's incredible historical development. Natural gas has rooted that date back to early civilisations. The Chinese were among the first to discover natural gas around 500 BC, using it to produce salt by evaporating brine. They used bamboo tunnels to move the gas and called it "fire from the earth". Similar eternal fires were built in Persia (modern-day Iran) using natural gas seeps, which were regarded as holy.[53] Koli & Rao[54] expressed that the early 19th century is when the current natural gas industry's basis began to take shape. The first commercial natural gas well was sunk by William Hart in Fredonia, New York, in 1821, starting the era of commercial natural gas production. Due to the high cost of long-distance transmission, the gas was initially only sometimes used for lighting. The controlled and effective

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50 İlhak, M. İ., Akansu, S. O., Kahraman, N., & Ünalan, S. (2018). Experimental study on an SI engine fuelled by gasoline/acetylene mixtures. Energy, 151, 707-714. https://doi.org/10.1016/j.energy. 2018.03.108

51 Choudhary, K. D., Nayyar, A., & Dasgupta, M. S. (2018). Effect of compression ratio on combustion and emission characteristics of CI Engine operated with Acetylene in conjunction with diesel fuel. Fuel, 214, 489-496. https://doi.org/ 10.1016/j.fuel.2017.11.051

52 Thodda, G., Madhavan, V. R., & Thangavelu, L. (2020). Predictive modelling and optimisation of performance and emissions of Acetylene fuelled CI engine using ANN and RSM. Energy Sources, Part A: Recovery, Utilisation, and Environmental Effects, 1-19. https://doi.org/ 10.1080/15567036.2020.1829191

53 Shaik, K. B., Masood, M., Ravi Kumar, K., & Srinivasa Rao, P. (2022). Experimental analysis of diesel engine with variable flow of acetylene gas in dual fuel mode. International Journal of Ambient Energy, 43(1), 3146-3153. https://doi.org/10.1080/01430750.2020.1797873

54 Koli, S. R., & Rao, Y. H. (2021). Study of low compression ratio on the performance of diesel engine in dual fuel operation with different flow rates of Acetylene. Fuel, 284, 118969. https://doi.org/10.1016/j. fuel.2020.118969

way the Bunsen burner burned natural gas made it ideal for use in residential and laboratory settings.

Likhanov and Lopatin[55] stated that the natural gas industry made incredible strides in the late 19th and early 20th centuries. Natural gas could be transported over long distances thanks to the National Fuel Gas Pipeline, built on a significant scale for the first time in Pennsylvania in 1891. The first commercial natural gas well in Texas was drilled in 1906, which resulted in the formation of the Texas Company (later known as Texaco) and a sharp increase in the state's natural gas production. Zhao et al.[56] showed that the identification of the Groningen gas field in the Netherlands in 1959 marked the beginning of one of the most significant discoveries in the history of natural gas. The Groningen field is one of the world's most important natural gas reserves, essential to Europe's energy supply. The liquefied natural gas (LNG) industry developed over the 20th century. Natural gas can be transformed into a liquid by chilling it to -260°F (-162°C), which results in a smaller volume and more practical and affordable long-distance transportation. Although the first LNG facility was built in West Virginia, the United States, in 1912, the large-scale commercial trade in LNG did not start until the 1960s.

Rossokhin & Anfilatov[57] addressed that natural gas has become a significant worldwide energy source in recent years. Its application has increased in several industries, including transportation, home heating, and industrial processes. Because it produces fewer carbon emissions than coal and oil, natural gas is a preferred option for cutting greenhouse gas emissions. With

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55 Likhanov, V. A., & Lopatin, O. P. (2018). The study of the process of combustion of the alcohol-fuel emulsions and natural gas in a diesel engine. International Journal of Applied Engineering Research, 13(3), 1703.

56 Zhao, Y., McDonell, V., & Samuelsen, S. (2019). Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner. International Journal of Hydrogen Energy, 44(23), 12239-12253. https://doi.org/10.1016/j.ijhydene.2019.03.100

57 Rossokhin, A. V., & Anfilatov, A. A. (2020, May). The effect of the use of natural gas on the emissivity of a flame in a cylinder of an automobile diesel engine. In IOP Conference Series: Materials Science and Engineering (Vol. 862, No. 6, p. 062065). IOP Publishing. https:// doi.org/10.1088/1757-899X/862/6/062065

the emergence of shale gas, natural gas production underwent a substantial transition in the twenty-first century. Large amounts of natural gas trapped in shale formations were released thanks to improvements in horizontal drilling and hydraulic fracturing, or "fracking" as it is more generally known.[58] The United States became the world's top natural gas producer due to the shale gas revolution, which also changed the global energy landscape. Likhanov and Rossokhin[59] stated that methane predominates in the complex mixture of hydrocarbon gases that make up natural gas. Understanding the makeup of natural gas is crucial for maximising its use, reducing its adverse environmental effects, and guaranteeing its secure handling and storage. Natural gas burns cleanly and may be used in various ways due to the high methane content and minor amounts of ethane, propane, and butane. Improved environmental sustainability and natural gas use efficiency require proper control of carbon dioxide and trace contaminants. With this understanding, we can fully utilise natural gas's potential as a dependable and eco-friendly energy source for various uses, including transportation and home heating. Zhao et al.[60] showed that using natural gas is changing as the world shifts to cleaner and more sustainable energy sources. Promising ways to cut carbon emissions include creating renewable natural gas (RNG) and incorporating natural gas with renewable energy systems. Furthermore, current research and financial investments in carbon capture, utilisation, and storage (CCUS) technology could improve natural gas's environmental credentials. Rossokhin and Anfilatov[61] explained that investigating alternative

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58 Raman, R., & Kumar, N. (2019). Experimental investigation to analyse the effect of induction length of diesel-acetylene dual fuel engine. Energy Sources, Part A: Recovery, Utilisation, and Environmental Effects, 1-15. https://doi.org/10.1080/15567036.2019.1663314

59 Likhanov, V. A., & Rossokhin, A. V. (2020). The impact of the use of compressed natural gas in a car diesel engine on the formation and oxidation of soot particles. In IOP Conference Series: Materials Science and Engineering (Vol. 734, No. 1, p. 012207). IOP Publishing. 10.1088/1757-899X/734/1/012207

60 Zhao, Y., McDonell, V., & Samuelsen, S. (2019). Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner. International Journal of Hydrogen Energy, 44(23), 12239-12253. https://doi.org/10.1016/j.ijhydene.2019.03.100

61 Rossokhin, A. V., & Anfilatov, A. A. (2020, May). The effect of using natural gas on the emissivity of a flame in a cylinder of an automobile diesel engine. In IOP

fuels has significantly accelerated the search for environmentally friendly transportation options. Natural gas has emerged as a promising alternative among these fuels for internal combustion engines (ICEs). Natural gas has many environmental benefits, including lower emissions and broad supply. This article explores natural gas's sustainability potential as a fuel for ICEs, outlining its advantages, drawbacks, and prospects for a greener future.

According to Likhanov & Rossokhin[62] Natural gas's lower carbon emissions when compared to more conventional fossil fuels like gasoline and diesel are one of its main benefits as a fuel for ICEs. Methane ($CH_4$), a hydrocarbon that emits fewer greenhouse gases when burned, makes up most of the natural gas. Natural gas can cut carbon dioxide ($CO_2$) emissions by about 20–30% compared to gasoline while also cutting nitrogen oxide (NOx) and particulate matter (PM) emissions by over 90%. Therefore, natural gas-powered vehicles substantially reduce climate change and enhance air quality. Likhanov and Lopatin[63] shared that the global abundance of natural gas deposits guarantees the long-term availability of this alternative fuel. Compared to other new technologies, switching to natural gas is more straightforward because of its accessibility and established distribution infrastructure. Natural gas can be obtained from native deposits, lowering a country's reliance on foreign oil and boosting energy security. Since internal combustion engines (ICEs) have dominated the vehicle industry for decades, using natural gas in an existing ICE is simple and requires few adjustments. Because of this compatibility, switching to natural gas as a fuel option can be done more efficiently without making expensive infrastructure or vehicle design changes.

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Conference Series: Materials Science and Engineering (Vol. 862, No. 6, p. 062065). IOP Publishing. 10.1088/1757-899X/862/6/062065

62 Likhanov, V. A., & Rossokhin, A. V. (2020). The impact of the use of compressed natural gas in a car diesel engine on the formation and oxidation of soot particles. In IOP Conference Series: Materials Science and Engineering (Vol. 734, No. 1, p. 012207). IOP Publishing. 10.1088/1757-899X/734/1/012207

63 Likhanov, V. A., & Lopatin, O. P. (2020, April). Development of a program for converting diesel engines to natural gas. In Journal of Physics: Conference Series (Vol. 1515, No. 5, p. 052002). IOP Publishing. 10.1088/1742-6596/1515/5/052002

The natural gas supply network and infrastructure for refuelling are also well-established, which increases the likelihood of widespread adoption in the short to medium term. Li et al.[64] explained that renewable natural gas (RNG) and conventional natural gas are gaining popularity as a sustainable fuel choice. RNG is created from organic waste disposed of in landfills, farms, and wastewater treatment facilities. This procedure captures and uses methane emissions that would otherwise be discharged into the atmosphere. It is possible to produce carbon-neutral or even carbon-negative emissions when using RNG, vastly boosting the viability of using natural gas as an ICE fuel. Akbarian et al.[65] thought that despite burning cleaner than gasoline or diesel, natural gas could leak methane throughout the extraction and transportation processes, a potent greenhouse gas. Proper monitoring and control mechanisms are required to reduce methane emissions throughout the natural gas supply chain. This problem can be solved, and the overall sustainability of natural gas as a fuel can be improved through technological developments and regulatory frameworks.[66] While natural gas offers a more environmentally friendly substitute for traditional fuels, electric mobility, fueled by renewable energy sources, is the long-term trend. The future viability and utility of ICEs fuelled by natural gas are questioned by the rising popularity of electric cars (EVs). However, natural gas can still be used as a transitional fuel, particularly in areas or for heavy-duty vehicles.[67]

Likhanov & Lopatin[68] focused on the fact that internal combustion engines can use natural gas as a sustainable alternative fuel, which lowers carbon

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64 Li, W., Liu, Z., & Wang, Z. (2016). Experimental and theoretical analysis of the combustion process at low loads of a diesel natural gas dual-fuel engine. Energy, 94, 728-741. https://doi.org/10.1016/j.energy.2015.11. 052

65 Akbarian, E., Najafi, B., Jafari, M., Faizollahzadeh Ardabili, S., Shamshirband, S., & Chau, K. W. (2018). Experimental and computational fluid dynamics-based numerical simulation of using natural gas in a dual-fueled diesel engine. Engineering Applications of Computational Fluid Mechanics, 12(1), 517-534. https://doi.org/10.1080/ 19942060.2018.1472670

66 Martins, J., & Brito, F. P. (2020). Alternative fuels for internal combustion engines. Energies, 13(16), 4086. https://doi.org/10.3390/en13164086

67 Tangoz, S., Ilhak, M. I., Akansu, S. O., & Kahraman, N. (2018). Experimental investigation of performance and emissions of an SI engine fueled by acetylene-methane and acetylene-hydrogen blends. Fresenius Environmental Bulletin, 27(6), 4174-85.

68 Likhanov, V. A., & Lopatin, O. P. (2018, November). Investigation of the speed regime of tractor diesel engine running on natural gas with recirculation. In IOP

emissions, improves air quality, and increases energy security. It is a workable short- to medium-term solution due to its compatibility with existing ICE technology and well-established infrastructure. However, the increasing shift to renewable energy sources and electric mobility emphasises the necessity for a thorough, all-encompassing strategy for sustainable transportation.[69] Natural gas can act as a temporary fix as efforts to decarbonise the transportation industry continue, supporting the overarching objective of creating a greener future.

## 5. ETHANOL AS AN ALTERNATIVE FUEL FOR INTERNAL COMBUSTION ENGINE

Chen et al.[70] discussed that since the beginning of engine development, Ethanol has been studied as a fuel for internal combustion engines. A structural and molecular formula of Ethanol is shown in Figure 4. An in-depth examination of the early ethanol fuel tests and key turning points that made it possible for it to be used in internal combustion engines is provided in this article. The study examined the fascinating history of Ethanol as an early alternative fuel, from the early experiments to the developments that laid the foundation for further study. Ouchikh et al.[71] presumed that gasoline was the primary fuel for internal combustion engines in the late 19th and

Conference Series: Materials Science and Engineering (Vol. 457, No. 1, p. 012011). IOP Publishing. 10.1088/1757-899X/457/1/012011

69 Singh, G., Sharma, S., Singh, J., Kumar, S., Singh, Y., Ahmadi, M. H., & Issakhov, A. (2021). Optimisation of performance, combustion and emission characteristics of acetylene aspirated diesel engine with oxygenated fuels: An Experimental approach. Energy Reports, 7, 1857-1874. https://doi.org/10.1016/j.egyr.2021.03.022

70 Chen, H., He, J., & Zhong, X. (2019). Engine combustion and emission fuelled with natural gas: a review. Journal of the Energy Institute, 92(4), 1123-1136. https://doi.org/10.1016/j.joei.2018.06.005

71 Ouchikh, S., Lounici, M. S., Tarabet, L., Loubar, K., & Tazerout, M. (2019). Effect of natural gas enrichment with hydrogen on combustion characteristics of a dual fuel diesel engine. International journal of hydrogen energy, 44(26), 13974-13987. https://doi.org/10.1016/ j.ijhydene.2019.03.179

early 20th centuries when the automotive industry started. However, even then, scientists and creators were aware of the potential of Ethanol as a workable substitute. Dr Nikolaus Otto, the creator of the four-stroke combustion engine, was one such visionary who experimented with several fuels, including Ethanol, to improve engine performance and efficiency.

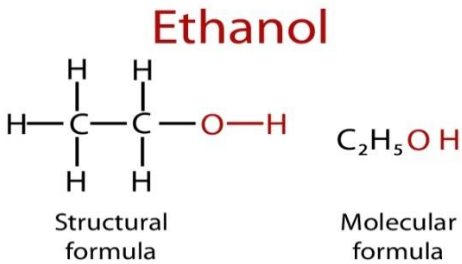


Figure 4: Diagram showing Ethanol's Structure and Molecular Formula Source: Lopatin [72]

Denatured Ethanol was used as fuel for motors during this time, demonstrating its potential. In the second part of the 20th century, Brazil became a global leader in ethanol fuel production. The Brazilian Government launched the "Proálcool" program to promote Ethanol as a fuel in response to the oil crises of the 1970s. Brazil has many sugarcane plantations, which provide an easy source of feedstock for ethanol manufacturing. Brazil's automotive sector saw a considerable transition due to the program's success, with a sizable proportion of vehicles now using high ethanol blends like E85. According to Ambrós et al.[73] Due to environmental concerns, there have been recent technological improvements and a greater emphasis on Ethanol as a renewable fuel source. Ethanol's efficiency and energy content have increased because of improved production and refining processes.

[72] Lopatin, O. P. (2020, April). Phenomenology of nitrogen oxides formation in a gas-diesel engine. In Journal of Physics: Conference Series (Vol. 1515, No. 4, p. 042009). IOP Publishing. 10.1088/1742-6596/1515/4/042009

[73] Ambrós, W. M., Lanzanova, T. D. M., Fagundez, J. L. S., Sari, R. L., Pinheiro, D. K., Martins, M. E. S., & Salau, N. P. G. (2015). Experimental analysis and modeling of internal combustion engine operating with wet Ethanol. Fuel, 158, 270-278. https://doi.org /10.1016/j.fuel.2015.05.009

Additionally, the potential market for Ethanol as a fuel has grown with the introduction of flexible fuel vehicles (FFVs), which can run on various ethanol-gasoline mixtures. On the way to Ethanol's mainstream acceptance, obstacles still exist. Infrastructure building, including ethanol fueling stations, is still significant. Concerns about the sustainability of large-scale ethanol production have also been raised due to land use, water use, and the effect on food prices.

Mofijur et al.[74] confirmed that early ethanol trials as an alternate fuel for internal combustion engines laid the groundwork for its use as a gasoline substitute. Before current worries about the environment and energy security existed, visionaries like Henry Ford and Samuel Morey saw its promise. Ethanol has been a reliable and renewable fuel for internal combustion engines ever since the first successful experiments, as well as the developments in Brazil and contemporary research. Ethanol's significance as an alternative fuel is set to grow with ongoing technical advancement and an emphasis on sustainable production, helping to ensure a more environmentally friendly and sustainable future for transportation. Malaquias et al.[75] expressed that Ethanol is a viable alternative to gasoline due to its potential environmental impact and energy security benefits. In Figure 5, the arrow shows the production pattern of fuel production from ethanol from the catalysis process to the end production. Since corn, sugarcane, and wheat are all renewable sources of plant material, Ethanol is a sustainable energy source. Ethanol has the potential to produce fewer greenhouse gas emissions when compared to gasoline. Although Ethanol emits carbon dioxide ($CO_2$) when burned, this $CO_2$ is considered a carbon cycle component because the plants used to make Ethanol absorb $CO_2$ while growing. As a result, it is

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74 Mofijur, M. G. R. M., Rasul, A. M., Hyde, J., Azad, A. K., Mamat, R., & Bhuiya, M. M. K. (2016). Role of biofuel and their binary (diesel–biodiesel) and ternary (ethanol–biodiesel–diesel) blends on internal combustion engines emission reduction. Renewable and Sustainable Energy Reviews, 53, 265-278. https://doi .org/10.1016/j.rser.2015.08.046

75 Malaquias, A. C. T., Netto, N. A. D., Filho, F. A. R., da Costa, R. B. R., Langeani, M., & Baêta, J. G. C. (2019). The misleading total replacement of internal combustion engines by electric motors and a study of the Brazilian ethanol importance for the sustainable future of mobility: a review. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41, 1-23.

thought that the net $CO_2$ emissions from the combustion of Ethanol are lower than those from the combustion of fossil fuels like gasoline.

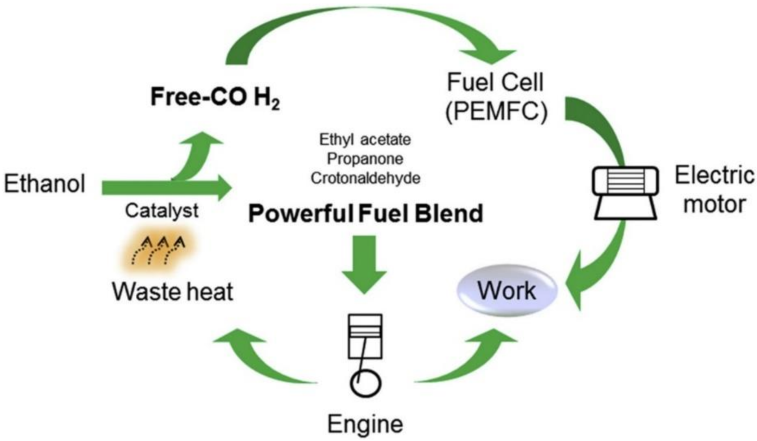


Figure 5: Diagram showing an Ideal Ethanol Engine
Source: Ilves et al. [76]

Mofijur et al.[77] stated that due to its chemical makeup, Ethanol is an oxygenate when added to gasoline, improving combustion and reducing the emissions of dangerous pollutants like carbon monoxide (CO). Other contaminants, including particulate matter and volatile organic compounds (VOCs), may also be lessened by Ethanol. Countries can increase energy security and diversify their energy sources by reducing their dependency on foreign oil imports by adding Ethanol to gasoline mixtures. Because they can run on any combination of Ethanol and gasoline, from lower concentrations like E10 (10% ethanol) to higher ones like E85 (85% ethanol), flex-fuel vehicles (FFVs) are compatible with Ethanol. FFVs allow customers to select fuel mixes based on cost and accessibility. However, da Silva Trindade and

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[76] Ilves, R., Küüt, A., & Olt, J. (2019). Ethanol as internal combustion engine fuel. In Ethanol (pp. 215-229). Elsevier. https://doi.org/10.1016 /B978-0-12-811458-2.00008-0

[77] Mofijur, M., Rasul, M. G., & Hyde, J. (2015). Recent developments on internal combustion engine performance and emissions fuelled with biodiesel-diesel-ethanol blends. Procedia Engineering, 105, 658-664. https://doi.org/10.1016/j .proeng.2015.05.045

dos-Santos[78] addressed that adopting Ethanol is not without problems. Since Ethanol has different storage and transportation requirements from gasoline, it is necessary to construct the essential infrastructure and distribution systems. However, many nations have invested in creating the required infrastructure, including ethanol distribution networks and filling stations. It is crucial to remember that various factors, such as governmental regulations, economic feasibility, and feedstock availability, affect Ethanol as an alternative fuel. Depending on local conditions and geographical circumstances, Ethanol as a gasoline substitute may have different advantages and disadvantages.[79]

Table 3 shows the evaluation of Ethanol compared with petrol.

**Table 3: Performance Evaluation of Ethanol compare to Petrol**

| Performance Evaluation | Ethanol | Petrol |
|---|---|---|
| **Energy Content** | Lower energy content than petrol results in lower mileage per gallon. | Higher energy content, leading to better mileage per gallon |
| **Octane Rating** | A higher-octane rating, typically around 100, improves performance and knock resistance. | A lower octane rating, typically around 87-93, may result in knocking in high-performance engines. |
| **Combustion Efficiency** | Ethanol has a higher heat of vaporisation, which can lead to better combustion efficiency. | Petrol has a lower heat of vaporisation, which may result in lower combustion efficiency. |
| **Greenhouse Gas Emission** | Ethanol has lower net greenhouse gas emissions than petrol, contributing to a reduced carbon footprint. | Petrol emits higher levels of greenhouse gases, contributing to higher carbon emissions. |
| **Engine** | Engines need modifications or | Petrol engines require no |

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78 da Silva Trindade, W. R., & dos Santos, R. G. (2017). Review on the characteristics of butanol, its production and use as fuel in internal combustion engines. Renewa ble and Sustainable Energy Reviews, 69, 642-651. https://doi.org/10.1016/j.rser. 2016.11.213

79 dos Santos Filho, D., Tschiptschin, A. P., & Goldenstein, H. (2018). Effects of ethanol content on cast iron cylinder wear in a flex-fuel internal combustion engine–A case study. Wear, 406, 105-117. https://doi.org/10.1016/j.wear.2018. 04.003

| | | |
|---|---|---|
| **Modification** | dedicated designs to run on higher ethanol blends, such as E85. | significant modifications to run on gasoline. |
| **Cold Start Performance** | Ethanol can be challenging to start in cold temperatures due to its higher vapour pressure. Cold-start aids are necessary. | Petrol performs better in cold temperatures, allowing for easier engine start-up. |
| **Availability** | The availability of Ethanol as a fuel may vary by region and depends on local production and distribution infrastructure. | Petrol is widely available globally and has an established distribution network. |
| **Cost** | The price of Ethanol can change based on several variables, such as feedstock availability and government subsidies. | Petrol prices are generally more stable and depend on global oil markets. |
| **Environmental Impact** | Ethanol is a renewable fuel, and its production can reduce fossil fuel consumption. However, it may have indirect environmental impacts, such as land use and water consumption for feedstock production. | Petrol is a non-renewable fossil fuel that contributes to greenhouse gas emissions and environmental degradation. |

Source: Author Work

## 6. BIOGAS AS A SUSTAINABLE ALTERNATIVE TO FUEL FOR INTERNAL COMBUSTION ENGINES

Organic material breaks down naturally to produce biogas, a renewable energy source. 'Natural' gas, a non-renewable energy source, should not be confused with biogas. Biogas replaces conventional natural gas to create combined electricity and heating for power plants—not for use in motor vehicles—after some minimal purification.[80] The purity of biogas must be increased to be used as fuel for cars. Capturing the gases resulting from this breakdown and using them as an energy source is less hazardous to the

80 Korberg, A. D., Skov, I. R., & Mathiesen, B. V. (2020). The role of biogas and biogas-derived fuels in a 100% renewable energy system in Denmark. Energy, 199, 117426. https://doi.org/10.1016/j.energy.2020. 117426

environment than letting them escape into the atmosphere because the biological material used to make biogas will naturally decay.[81] Biogas is produced by anaerobic bacteria, which break down organic matter in four stages: hydrolysis, acidification, synthesis of acetic acid, and creation of methane. Anaerobic digestion produces gaseous byproducts called biogas, whose production is highly dependent on the substrate (raw material). Fertiliser and waste are mixed in the facility's intake tank. They are then heated to 38–52°C/100–125.6°F and poured into the digester, where biogas is produced, as shown in Figure 6. The digested slurry from the fermentation of the biomass remains in the digester for two to three weeks before being used as crop fertiliser. Methane and hydrogen are explosive and can also be oxidised with oxygen. Biogas can now be used as fuel for fuel cells and other heating applications, such as cooking, thanks to this energy release. The energy in the gas can also be transformed into heat and power by using it in a gas engine.[82] Casanovas et al.[83] proposed that humans have used biogas as a sustainable energy source for ages. It is a flexible and sustainable energy alternative that uses organic waste's strength to transform it into a helpful resource. Many ancient cultures used biogas thousands of years ago. The Vedas, early Hindu writings, which described the usage of "gobar gas" or "cow dung gas," are where the idea of biogas originated in India. The Indian farmers discovered that gathering animal waste, such as cow dung, and storing it in a sealed container could create combustible gas for lighting and cooking. Galindo et al.[84] attested that the first anaerobic digester was created by a French scientist named Eugene Schliep in the middle of the 19th century, ushering in the modern era of biogas. The authors made a method to decompose organic material without oxygen, creating biogas as a by-product.

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81 Ciuła, J., Gaska, K., Iljuczonek, Ł., Generowicz, A., & Koval, V. (2019). Energy efficiency economics of conversion of biogas from the fermentation of sewage sludge to biomethane as a fuel for automotive vehicles. Architecture, Civil Engineering, Environment, 12(2), 131-140. https://doi.org/10.21307/acee-2019-029

82 Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Biogas production and applications in the sustainable energy transition. Journal of Energy, 2022, 1-43. https://doi.org/10.1155/2022/8750221

83 Casanovas, A., Divins, N. J., Rejas, A., Bosch, R., & Llorca, J. (2017). Finding a suitable catalyst for on-board Ethanol reforming using exhaust heat from an internal combustion engine. International Journal of Hydrogen Energy, 42(19), 13681-13690. https://doi.org/10.1016/ j.ijhydene.2016.11.197

84 Galindo, J., Dolz, V., Royo-Pascual, L., Haller, R., & Melis, J. (2016). Modeling and experimental validation of a volumetric expander suitable for waste heat recovery from an automotive internal combustion engine using an organic rankine cycle with Ethanol. Energies, 9(4), 279. https://doi.org/10.3390/en9040279

This breakthrough opened the door for more developments in biogas technology. Oswald Schmiederer, a German engineer and microbiologist, made substantial contributions to biogas research in the early 20th century. Authors created and constructed sizable biogas plants that used industrial and agricultural waste to produce electricity. The author's work established the groundwork for biogas to be used commercially as a reliable energy source.

Figure 6: The Schematic Diagram of the Biogas Production Process

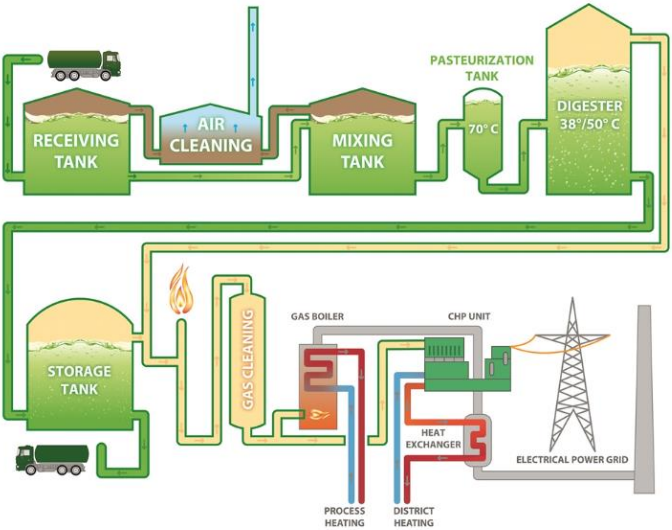


Figure 6: The Schematic Diagram of the Biogas Production Process
Source: Galindo et al.[85]

Sato et al.[86] explained that biogas as a sustainable energy source attracted increased attention due to the oil crisis and escalating environmental concerns in the 1970s. Infrastructural and scientific investments in biogas have been made by nations including Germany, Sweden, and Denmark. The emphasis

85 Ibid Galindo et al.

86 Sato, A. G., Silva, G. C., Paganin, V. A., Biancolli, A. L., & Ticianelli, E. A. (2015). New, efficient and viable system for ethanol fuel utilisation on combined electric/internal combustion engine vehicles. Journal of power sources, 294, 569-573. https://doi.org/10.1016/j.jpowsour.2015.06.086

switched to biogas for electricity generation, heat production, cooking, and lighting. The first large-scale biogas plant was built in Germany in 1979, representing one of the most crucial turning points in the modern history of biogas. This facility generated biogas from manure, organic, and agricultural waste to generate heat and electricity. Due to the project's success, biogas facilities have rapidly expanded throughout Europe and other parts of the world. Qian et al.[87] presented that biogas has various environmental advantages as a desirable renewable energy source. It mainly aids in lowering greenhouse gas emissions. Methane, a potent greenhouse gas, is released when organic waste decomposes. However, the methane emissions are significantly decreased by trapping this waste in anaerobic digesters and turning it into biogas. Additionally, Dobslaw et al.[88] proposed that biogas can lessen dependency on non-renewable energy sources by substituting fossil fuels in various applications. It may generate energy and heat, cook food, power vehicles, and even serve as a renewable natural gas supply for piping into existing gas systems. Recent technical developments have improved the effectiveness and cost-efficiency of biogas production. Co-digestion, which involves mixing various kinds of organic waste in the digester, has been implemented and has improved the procedure overall while increasing biogas output. Furthermore, the conversion of biogas into biomethane, a high-quality gas with qualities resembling those of natural gas, has expanded the possibilities for its usage in the current gas infrastructure. Yağlı et al.[89] explained that biogas had been used as an internal combustion engine fuel since the early 19th century. Étienne Lenoir, a French inventor, created the first functional internal combustion engine in 1806, which used coal gas, a forerunner to biogas. The investigation of gaseous fuels for use in engines began with this. Modifications are made to the fuel delivery system, ignition timing, and compression ratio to achieve optimum performance and

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[87] Qian, Y., Sun, S., Ju, D., Shan, X., & Lu, X. (2017). Review of the state-of-the-art of biogas combustion mechanisms and applications in internal combustion engines. Renewable and Sustainable Energy Reviews, 69, 50-58. https://doi.org/10.1016/j.rser.2016.11.059

[88] Dobslaw, D., Engesser, K. H., Störk, H., & Gerl, T. (2019). Low-cost process for emission abatement of biogas internal combustion engines. Journal of Cleaner Production, 227, 1079-1092. https://doi.org/10.1016 /j.jclepro.2019.04.258

[89] Yağlı, H., Koç, Y., Köse, Ö., Koç, A., & Yumrutaş, R. (2021). Optimisation of simple and regenerative organic Rankine cycles using jacket water of an internal combustion engine fuelled with biogas produced from agricultural waste. Process Safety and Environmental Protection, 155, 17-31. https://doi.org/10.1016/j.jclepro.2019.04.258

efficiency. Organic waste products are widely available and used to create biogas. As a result of its manufacture, methane emissions are decreased, and a circular economy is encouraged. Burning biogas produces much less greenhouse gas pollution than burning fossil fuels. Methane from organic waste can be extracted and used to help slow down climate change. Jung et al.[90] opposed the idea that another important topic is energy independence. Producing biogas enables distributed energy production, which lessens reliance on conventional energy sources. This encourages local communities to be resilient and self-sufficient in terms of energy. Additionally, biogas offers a practical waste management option because organic waste can be recycled into a valuable energy source.

Although Bora et al.[91] stated that biogas has much potential as an alternative fuel for internal combustion engines, several issues still need to be resolved before it can be widely used. It is challenging to employ biogas extensively in transportation applications due to the restricted availability of biogas refuelling infrastructure. Infrastructure development investments are essential to help biogas become a viable fuel option. A steady supply of organic waste feedstock is necessary for the continuous production of biogas. Proper waste management practices and partnerships with the agricultural, industrial, and municipal sectors are required to maintain a sustainable supply chain. Santos et al.[92] explained that internal combustion engines must be particularly adapted or created to function well with biogas. Retrofitting older machines can be expensive, and there are few speciality bio-gas engines yet. Biogas has a lower energy density than conventional fuels, reducing a vehicle's range. Due to this restriction, biogas applications must be carefully considered, and cutting-edge storage and distribution systems must be created. Mukumba et

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90 Jung, C., Park, J., & Song, S. (2015). Performance and NOx emissions of a biogas-fueled turbocharged internal combustion engine. Energy, 86, 186-195. https://doi.org/10.1016/j.energy.2015.03.122

91 Bora, D., Barbora, L., Borah, A. J., & Mahanta, P. (2021). A Comparative Assessment of Biogas Upgradation Techniques and Its Utilisation as an Alternative Fuel in Internal Combustion Engines. In Alternative Fuels and Advanced Combustion Techniques as Sustainable Solutions for Internal Combustion Engines (pp. 95-115). Singapore: Springer Singapore.

92 Santos, N. D. S. A., Roso, V. R., Malaquias, A. C. T., & Baeta, J. G. C. (2021). Internal combustion engines and biofuels: Examining why this robust combination should not be ignored for future sustainable transportation. Renewable and Sustainable Energy Reviews, 148, 111292. https://doi.org/10.1016/j.rser.2021.111292

al.[93] stated that biogas, produced from organic waste, is an environmentally friendly and renewable energy source for internal combustion engines. It is an appealing alternative fuel choice because of its ability to lower greenhouse gas emissions, advance waste management, and increase energy independence. The widespread use of biogas in internal combustion engines will depend on addressing infrastructure issues, providing a steady feedstock supply, and making additional engine breakthroughs. Biogas can be critical in decarbonising transportation and advancing a more sustainable energy environment as the globe transitions to a greener future. The different criteria for biogas analysis with petrol are given in Table 4.

Table 4: Comparative Performance Criteria of Bio-Gas to Petrol

| PERFORMANCE CRITERIA | BIO GAS | PETROL |
|---|---|---|
| Octane Rating | Lower | Higher |
| Combustion Efficiency | Lower | Higher |
| Power Output | Lower | Higher |
| Torque | Lower | Higher |
| Ignition Characteristics | Require Advance Ignition System | Standard Ignition System |
| Engine Knock | Lower Propensity for knock | Higher Propensity for knock |
| Emission | Lower | Higher |
| Emissions (Pollutants) | Lower Emission NOx HC and CO | Higher Emission NOx, HC and CO |
| Fuel Consumption | Higher | |
| Fuel System Compatibility | Required Modified fuel system | Standard |
| Stability | Reduced | Standard |
| Maintenance | Potential for Increased Maintenance | Standard Maintenance |

Source: Carnevale & Lombardi[94]

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93 Mukumba, P., Makaka, G., & Mamphweli, S. (2016). Biogas technology in South Africa, problems, challenges and solutions. International Journal of Sustainable Energy and Environmental Research, 5(4), 58-69.

94 Carnevale, E., & Lombardi, L. (2015). Comparison of different possibilities for biogas use by Life Cycle Assessment. Energy Procedia, 81, 215-226. https://doi.org/10.1016/j.egypro.2015.12.088.

## 7. CHALLENGES AND WAY FORWARD OF HYDROGEN, ACETYLENE, NATURAL GAS, ETHANOL AND BIO-FUEL AS AN ALTERNATIVE FUEL

Hydrogen has garnered considerable interest as an eco-friendly and effective substitute for traditional fuels, holding promise in curbing greenhouse gas emissions and alleviating the environmental consequences associated with conventional energy sources.[95] Possessing a remarkable energy density and emitting solely water vapour upon combustion, hydrogen can bring about a transformative shift in numerous industries, ranging from transportation to power generation. Nevertheless, several hurdles necessitate resolution before embracing hydrogen as a widely adopted alternative fuel. An inherent obstacle lies in the production of hydrogen itself, where the prevailing method predominantly relies on fossil fuels, consequently contributing to carbon emissions.[96] For hydrogen to embody sustainability, a fundamental shift towards renewable energy sources must transpire in its production. Embracing methodologies like electrolysis driven by wind or solar power, recognised as green hydrogen, holds immense potential in substantially diminishing the carbon footprint linked with hydrogen generation. Furthermore, progressions in electrolysis technology alongside the integration of catalysts can enhance the process's efficiency and cost-effectiveness.[97] Evaluating Ethanol, biofuel, natural gas, hydrogen, and Acetylene as feasible and sustainable alternatives for internal combustion engines emphasises their potential to support a future where transportation is

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95 Akram, F., Fatima, T., Ibrar, R., & ul Haq, I. (2024). Biohydrogen: Production, promising progressions and challenges of a green carbon-free energy. Sustainable Energy Technologies and Assessments, 69, 103893. https://doi.org/10.1016/j.seta.2024.103893.

96 Sikiru, S., Oladosu, T. L., Amosa, T. I., Olutoki, J. O., Ansari, M. N. M., Abioye, K. J., ... & Soleimani, H. (2024). Hydrogen-powered horizons: Transformative technologies in clean energy generation, distribution, and storage for sustainable innovation. International Journal of Hydrogen Energy, 56, 1152-1182. https://doi.org/10.1016/j.ijhy dene.2023.12.186

97 Islam, A., Islam, T., Mahmud, H., Raihan, O., Islam, M. S., Marwani, H. M., ... & Awual, M. R. (2024). Accelerating the green hydrogen revolution: A comprehensive analysis of technological advancements and policy intervene tions. International Journal of Hydrogen Energy, 67, 458-486. https://doi.org /10.1016/j.ijhydene.2024.04.142.

environmentally benign and sustainable. Each fuel has unique qualities and presents various benefits and difficulties.

Hydrogen must overcome infrastructure-related challenges for widespread use connected to production, storage, and delivery. Hydrogen is known for having a high energy content and being emission-free. Although Acetylene is less frequently used, it demonstrates excellent combustion efficiency.[98] It may be helpful in some situations, but it must be handled and stored cautiously due to safety considerations. Natural gas, a plentiful fossil fuel, has fewer emissions than conventional fuels, allowing for cleaner burning and producing fewer greenhouse gases. With a high-octane rating, compatibility with current engines, and lower greenhouse gas emissions, Ethanol from renewable resources like sugarcane or corn offers a practical substitute for fossil fuels. However, a careful analysis is required due to its lower calorie content and potential effects on food production. Bio-fuels, which include biodiesel and bioethanol made from biomass, have a positive environmental impact, low emissions, and are compatible with standard engines. However, production scalability, feedstock accessibility, and potential land use issues necessitate careful management. Energy content, combustion efficiency, emissions profile, engine adaptability, infrastructure needs, and overall sustainability must be considered when evaluating the performance of various alternative fuels. Each fuel has advantages and disadvantages that call for thorough study, development, and supportive laws. Continuous improvement in fuel production, engine technology, and supportive legislative frameworks are necessary if sustainable alternative fuels for internal combustion engines are to be used to their full potential. Collaboration between researchers, industry stakeholders, and policymakers is crucial to addressing technical, economic, and environmental issues.

[98] Soleimani, A., Hosseini Dolatabadi, S. H., Heidari, M., Pinnarelli, A., Mehdizadeh Khorrami, B., Luo, Y., ... & Brusco, G. (2024). Progress in hydrogen fuel cell vehi cles and up-and-coming technologies for eco-friendly transportation: an interna tional assessment. Multiscale and Multidisciplinary Modeling, Experiments and Design, 1-20. https://doi.org/10.1007/s41939-024-00482-8

## 8. LEGAL STRUCTURE OF HYDROGEN AND BIO-FUEL AS ALTERNATIVE FUELS FOR INTERNAL COMBUSTION ENGINES IN NIGERIA

The 1999 Constitution of the Federal Republic of Nigeria and the Petroleum Industry Act 2021 are cardinal, among other legislation that govern Nigeria's oil and gas sector[99]. A critical piece of legislation, the Petroleum Industry Act (PIA) 2021, aims to promote host communities, provide a legal and regulatory framework for the industry, and address other pertinent issues in the upstream, midstream, and downstream sectors.[100] The Act greatly reorganised the industry, removing needless duplication and harmonising all relevant laws. The industry has seen a surge in Foreign Direct Investment (FDI) due to the PIA in response to security concerns and infrastructure deficiencies. Nevertheless, since hydrogen and biofuel have been proven to be viable replacements for petroleum used for internal combustion engines, the Government can also extend the policy framework employed in the PIA Act to enable Nigeria's economy to benefit from its utilisation[101]. It is still unclear how investments in fossil fuels will be affected by the upcoming energy transition.[102] The petroleum business in Nigeria has seen a substantial transformation because of the PIA, making it a more secure and efficient sector. However, using petroleum products is not ecologically beneficial to

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99 Borha D.O.E & Olujobi, OJ., An Examination of the Petroleum Industry Act 2021: Prospects, Challenges, and the Way Forward, Taylor & Francis, F1000Research (2023), 12:551, <https://doi.org/10.5256/f1000 research.153263. r197203> accessed August 20,2024.

100 Dhali, M., Hassan, S., & Subramaniam, U. (2023). Comparative analysis of oil and gas legal frameworks in Bangladesh and Nigeria: a pathway towards achieving sustainable energy through policy. Sustainability, 15(21), 15228. https://doi.org/10. 3390/su15211 5228.

101 Olujobi, Olusola Joshua et al (2023), Legal Responses to Energy Security and Sustainability in Nigeria's Power Sector Amidst Fossil Fuel Disruptions and Low Carbon Energy Transition, Heliyon, (2023), 9(7), e17912. < https://www.cell.com /heliyon/fulltext/S2405-8440(23)05120-4> (accessed August 20, 2024).

102 Olujobi, O. J. (2023). Nigeria's upstream petroleum industry anti-corrup tion legal framework: the necessity for overhauling and enrich ment. Journal of money laundering control, 26(7), 1-27. https://doi.org/ 10.1108/JMLC-10-2020-0119.

the environment[103]. The Nigerian Petroleum Minister (MoP) administrates and governs the country's petroleum sector in conjunction with the approval of regulatory institutions such as the Nigerian Upstream Petroleum Commission and the Nigerian Midstream and Downstream Petroleum Authority under the Petroleum Industry Act 2021 (PIA). The Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA) governs the midstream and downstream petroleum operations. The Nigerian Upstream Petroleum Regulatory Commission regulate upstream petroleum activities. the Nigerian National Petroleum Company Limited (NNPC Limited) was founded as a legal, commercial entity with the power to oversee and manage its business affairs, sell its shares and declare and pay dividends to its shareholders without relying on the Federal Government for funds and set aside 20% of its revenues for future use. Figure 7 shows the regulatory authority responsible for developing and maintaining the oil and gas sector.[104] However, this study projects that since there are bodies responsible for regulating the existing petroleum product, the same bodies can be incorporated to develop the policy and techniques to regulate fuel production from hydrogen and biofuel for sustainable operations.

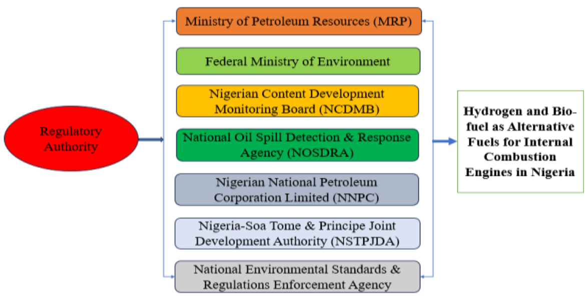


Figure 7: Nigeria Industry of Petroleum Regulatory Authority
Source: Author structural design

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[103] Olujobi, O.J., Nigeria's Climate Change Act 2021: A Pathway to Net-Zero Carbon Emission, Energy Security and Sustainability, Environ mental Science and Pollution Research, (2024), DOI 10.1007/s11356-024-33347-1 accessed March 21, 2024.

[104] Okokpujie, I. P., & Tartibu, L. K. (2023). Production Quality and Operation Management as a Sustainable Tool for Advance Development of the Food and Beverages Manufacturing Industry in Nigeria. In E3S Web of Conferences (Vol. 430, p. 01257). EDP Sciences. https://doi.org/10.1051/e3sconf/202343001257

The second goal is to enhance Nigeria's oil and gas resources management and foster industry expansion. The Act guarantees excellent Governance, transparency, and sustainable development. The Nigerian Upstream Petroleum Regulatory Commission is responsible for data and analysis about upstream petroleum activities, adhering to global best practices.[105] The Minister may declare a frontier basin a general onshore area if petroleum is found there, utilising new fiscal arrangements for licences and leases. A lease or licence may only be obtained by businesses duly incorporated under the Companies and Allied Matters Act 2020. Licences and permits may be approved, renewed, modified, or extended by the Nigerian Upstream Petroleum Regulatory Commission. For Nigeria's diverse economy centred on gas and crude oil, granting petroleum licences and leases is a significant turning point.[106] Figure 8 illustrates the governance frameworks that define how individuals engage with the organisation, with the regulating authority and other relevant interested parties, to steer and oversee the processes that occur very closely.

Nigeria's Governance has a strong structure that backs the production and utilisation of oil and gas (petroleum products) in Nigeria.[107] This study will recommend implementing some techniques for properly developing a strong policy for Nigeria's hydrogen and bio-fuel plant operations.[108] A further approach is multi-criteria decision analysis (MCDA), another unique technique the Government should apply to address the policy concerns surrounding hydrogen and biofuel production and use in the transportation sector.

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105 Ali-Nakyea, A., Atuguba, R. A., Saibu, O. M., & Mohammed, N. A. (2023). Legal, regulatory, and fiscal arrangements in the oil and gas industry in emerging and developing countries. In The Economics of the Oil and Gas Industry (pp. 43-57). Routledge.

106 Olujobi, O. J. (2021). Deregulation of the downstream petroleum industry: An overview of the legal quandaries and proposal for improvement in Nigeria. Heliyon, 7(4). https://doi.org/10.1016/j.heli yon.2021.e06848

107 Otu, M., Anyatang, B. F., Kooffreh, B., & Ugbe, R. O. (2024). An Appraisal of the Legal Frameworks and Policy Shift in the Nigerian Energy Sector. Nature Environment & Pollution Technology, 23(2).

108 Kügemann, M., & Polatidis, H. (2024). Multi-criteria decision analysis of alternative fuel buses: methodology and case-study. International Journal of Green Energy, 1-21. https://doi.org/10.1080/15435075.2024.2316768.

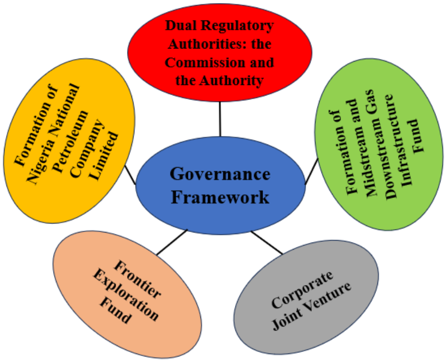


Figure 8: The Industrial Structural Framework of Oil and Gas for Nigeria's Governance.Source: Author Design

This approach will make it easier for decision-makers to comprehend the economic value of hydrogen and biofuel for internal combustion engines in this nation and facilitate the completion of fruitful research on the subject.[109] This will assist in carrying out quality research on hydrogen in several application sectors and offer an appropriate location for the hydrogen and bio-fuel business.[110] Thus, the nation will greatly benefit from using this method to research the contribution of hydrogen and biofuel to economic growth and to formulate sustainable policies.[111]

Nonetheless, this MCDA has been utilised in several academic disciplines to address selection and chain distribution issues. Additionally, its effectiveness

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109 Okokpujie, I. P., Tartibu, L. K., & Omietimi, B. H. (2023). Improving the Maintainability and Reliability in Nigerian Industry 4.0: Its Challenges and the Way Forward from the Manufacturing Sector. International Journal of Sustainable Development & Planning , 18(8).

110 Jafarnejad, E., Makui, A., Hafezalkotob, A., & Aghsami, A. (2024). Governance intervention policies in the production competition of biofuels and fossil fuels: a pathway to sustainable develop ment. Operations Management Research, 1-23. https://doi.org/ 10.1007/s12063-024-00441-z.

111 Yamaji, D. M., Amâncio-Vieira, S. F., Fidelis, R., & Do R. Contani, E. A. (2024). Decision-making in biogas production projects: Paradigms and prospec tion. Journal of the Air & Waste Management Association, (just-accepted). Pages 416-438. https://doi.org/10.1080/10962247.2024.233 8747.

in the decision-making process has been demonstrated.[112] When implementing the policy, it should take into account the following three factors using MCDA:

i. Appropriate rules for growing hydrogen and biofuel include how it is produced, how it is safely stored, and how it is utilised.
ii. The transportation, oil and gas industries must implement a legal structure for hydrogen and bio-fuel implementation methods that outlines the steps hydrogen and bio-fuel end users must take in specific crucial applications.[113]
iii. The stakeholders should demonstrate the most appropriate locality or community in Nigeria where the plant will be cited using the MCDA in conjunction with laboratory testing.[114]

As a result, the transportation industry's use of hydrogen fuel and bio-fuel as alternative fuels to drive the internal combustion engine will go well without a hitch and significantly boost the country's economy.

## 9. CONCLUSION AND RECOMMENDATIONS

The performance assessment of biofuel and hydrogen as sustainable alternative fuels for internal combustion engines and their legal structure in Nigeria has been conducted. The study highlights their potential to support a cleaner and more ecologically friendly transportation sector. The continuous improvements in fuel production, engine technologies, and cooperative efforts are essential for enabling an internal combustion engine-powered

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[112] Okokpujie, I. P., Okonkwo, U. C., Bolu, C. A., Ohunakin, O. S., Agboola, M. G., & Atayero, A. A. (2020). Implementation of multi-criteria decision method for selection of suitable material for development of horizontal wind turbine blade for sustainable energy generation. Heliyon, 6(1). https://doi.org/10.1016/j.heliyon .2019.e03142.

[113] Toplicean, I. M., & Datcu, A. D. (2024). An Overview on Bioeconomy in Agricultural Sector, Biomass Production, Recycling Methods, and Circular Economy Considerations. Agriculture, 14(7), 1143. https://doi.org/10.3390 /agriculture14071143.

[114] Okokpujie, I. P., Okokpujie, K., Omidiora, O., Oyewole, H. O., Ikumapayi, O. M., & Emuowhochere, T. O. (2022). Benchmarking and Multi-Criteria Decision Analysis Towards Developing a Sustainable Policy of Just in Time Production of Biogas in Nigeria. International Journal of Sustainable Development & Planning, 17(2). https://doi.org /10.18280/ijsdp.170208.

sustainable future. Therefore, the study has the following conclusion and recommendations:

1. Further investigations are needed to explore the optimal blend ratios, combustion strategies, and emission control techniques to fully exploit the potential of hydrogen and biofuel as a fuel in CI engines.
2. The main research priorities should be the development of cutting-edge fuel production technologies, investigating engine modifications, and advancing pollution control systems.
3. The stakeholders must enact a stringent legal framework and formulate policies to guide hydrogen and biofuel production, safety, storage and utilisation. Therefore, the study recommends the application of multi-criteria analysis for sustainable development.
4. Awareness of the need to use hydrogen refuelling stations to enable hydrogen-powered vehicles, the expansion of natural gas distribution networks, and the accessibility of biofuel blends at regular fuelling stations are essential.