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Alternate Fuel Vehicle Technology

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Abstract: ***This paper explores alternative fuels for vehicles beyond battery-electric options, focusing on biofuels, hydrogen, natural gas, and hybrid vehicles. Biofuels, derived from living organisms, offer a renewable energy source that can significantly reduce greenhouse gas emissions and promote sustainable energy solutions. Discussions include global interest in biofuels, bioethanol as a transportation fuel, production sources, the bioethanol economy, and limitations on bioethanol production. Hydrogen presents a compelling alternative to fossil fuels due to its versatility and potential to be produced from various resources. The paper covers hydrogen trends, production, distribution, storage, fuel cells, and the transition towards a hydrogen-based economy. Additionally, natural gas, abundant and cleaner than fossil fuels, is emerging as a promising alternative for vehicles. The section on natural gas vehicles (NGVs) discusses the market, benefits, reserves, limitations, and infrastructure challenges associated with NGVs. Finally, the paper compares hybrid vehicles (HEVs) and plug-in hybrid vehicles (PHEVs), highlighting their propulsion systems, energy sources, electricity generation, and energy savings. The conclusion emphasizes that alternative fuels represent a sustainable future for the transportation sector, albeit with significant challenges such as infrastructure development and cost competitiveness. Continued research and development efforts are crucial to address these challenges and promote the widespread adoption of alternative fuels for vehicles.***

Keywords: Alternate Vehicle Fuels, Alternate Fuels, Alternate Transportation of Fuels, Sustainable Vehicle Fuels, Bioethanol Fuel, Hydrogen Fuel, Natural Gas vehicle, Compressed Natural Gas vehicle, CNG, Hybrid Vehicles, Plug-in Hybrid Vehicles, HEV, PHEV.

1. Introduction

Petroleum has been the primary fuel for vehicles to date. However, as a fossil fuel, petroleum is a limited resource. Therefore, there has been ongoing exploration of alternative fuels for vehicles. Options include battery-electric, biofuel, hydrogen, natural gas, and hybrid vehicles. Battery-Electric vehicles are so far the most widespread in this list. However, alternative fuels such as biofuel, hydrogen, natural gas, and hybrid vehicles boast higher energy densities compared to battery vehicles. This difference suggests significant potential for exploring these alternative options. The paper focuses on delving into alternative fuels for vehicles beyond those solely powered by either gasoline or electric batteries.

1.1 BioFuels (Bio Alcohol & Ethanol)

Biofuel, the name itself suggests that it is produced from living organisms. Biofuels are primarily made from plant matter such as agricultural crops, forestry by-products, etc. The interest in biofuels has been growing at a decent pace, similar to other alternative fuels. The reasons are mainly common, but biofuel happens to satisfy most of them: growing oil prices, limited oil reserves, and negative impact on the climate, among others. The use of biofuels can significantly reduce greenhouse gas emissions, provide a sustainable clean energy source, and increase agricultural income for rural development.

Biofuels are attractive for three main reasons: Firstly, they are a renewable resource with significant development potential in the future. Secondly, they show no net release of carbon dioxide into the environment. Thirdly, they hold economic potential. Bioethanol, a type of biofuel, is ethyl alcohol with a chemical composition of C2H5OH. It also has value as an oxygenate in clean-burning gasoline to reduce vehicle exhaust emissions. Bioethanol boasts a higher-octane number (108), higher flame speeds, broader flammability limits, and higher heats of vaporization. These characteristics allow bio-alcohols a higher compression ratio and a shorter burn time, resulting in higher efficiency than gasoline in an Internal Combustion engine. Overall, biofuels present a promising avenue for sustainable and efficient energy solutions.

a) Global Interest

Biofuels are attracting growing interest around the continents, with some countries showing commitments to biofuels as an alternative to petroleum, which helps in reducing greenhouse gas emissions. The USA, Brazil, and many European countries have taken biofuels very seriously. Global production of bioethanol increased from 17,335.2 million liters in 2008 to 23,429 million liters in 2013. The emphasis on bioethanol is remarkable; the USA and Brazil lead in the production of bioethanol, and constant efforts are made by these countries to encourage transport vehicles to use bioethanol. Bioethanol is used as a mixture in E85, where E85 contains 85% bioethanol and 15% gasoline. In the USA, the Energy Policy Act of 2005 (EPAct 2005) is one of the most significant steps in the history of biofuels in the USA. Back in 2005, biofuels constituted just 1% of the total fuel used in the country, with a target to increase this to 5% by 2012. In Brazil, there is a long history with biofuels; it all started in 1975 as an alternative to expensive gasoline. By 2009, 80% of Brazil's automobile production had flexible-fuel capability. With bioethanol widely available at almost all gas stations in the country, Brazilian consumers currently choose primarily between anhydrous bioethanol/gasoline and a 25% bioethanol/gasoline blend.

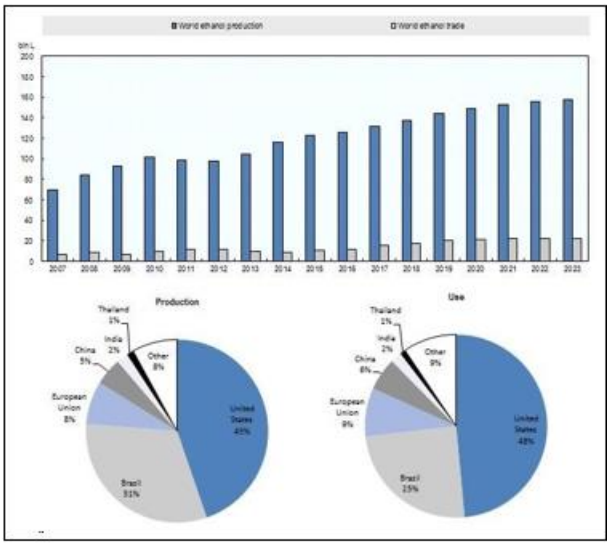

Figure 1: Reports Predicts Growth in Ethanol Production | Source: [25] ethanolproducer.com

Europe has always taken initiatives to support renewable energy technologies. Subsidizing taxes on biofuels was a major and helpful step to encourage the use of biofuels. Germany is the leading country in the production of biofuels among European countries. Various countries in Europe have different targets related to various renewable energies. Similar serious steps are taken in emerging markets like China, India, and the rest of the world.

The OECD-FAO (Organization for Economic Co-operation and Development and the Food and Agricultural Organization) predicts that the use and production of biofuels will increase significantly through 2023. It also predicts that ethanol prices will increase by 9%, depending on inflation rates and petroleum prices. The image above shows the global production and distribution of ethanol based on OECD-FAO's work.

b) Bioethanol as a transportation fuel

Bioethanol and bioethanol/gasoline blends have been used for a long time. In Germany and France, it has been utilized since 1894, while Brazil began using it as a transportation fuel in 1925. Bioethanol was widely employed in Europe and the United States until the early 1900s. However, its potential was largely ignored until the oil crisis of the 1970s, as it became more expensive to produce than petroleum-based fuel, particularly after World War II. Since the 1980s, bioethanol has been increasingly utilized as an alternative fuel for transportation. Countries like Brazil and the United States have played significant roles in promoting domestic bio-ethanol consumption and production. Furthermore, in addition to energy considerations, it has also been promoted as an environmentally friendly practice.

Bioethanol can be utilized in various ways as a transportation fuel, either directly or blended with gasoline. It can be added to gasoline in different proportions and burned in traditional combustion engines without modification. For instance, it can be blended with gasoline at a ratio of 10% bioethanol to 90% gasoline, known as E10. In Brazil, it is combined with gasoline in a mixture called gasohol (24% bioethanol and 76% gasoline). Additionally, 5% bioethanol is blended with petrol under the EU quality standard EN 228. With engine modification, bioethanol can be used in higher proportions, such as in E85 (85% bioethanol).

Bioethanol contains 35% oxygen, making it an oxygenated fuel. This characteristic aids in reducing particulates in exhaust emissions and significantly decreases NOx emissions. The use of bio-ethanol blended fuel in automobiles can substantially reduce petroleum consumption and greenhouse gas emissions from exhaust. It also increases the oxygen content in gasoline, thereby improving combustion and reducing exhaust emissions.

c) Production and sources for Bioethanol

Remarkable research is being conducted worldwide to discover new and cost-effective sources for the production of bio-ethanol. Recently, crops such as sugar cane, corn, and soybeans have been heavily studied for generating renewable energy. While this appears highly advantageous, there are concerns, such as residual waste left after fuel production, potential food shortages, and soil depletion on farms.

Bio-ethanol feedstock can be divided into three major parts:

- Sucrose-containing feedstock, which includes sugar cane, sugar beet, sweet sorghum, and fruits.
- Starchy materials, which include corn, milo, wheat, rice, potatoes, cassava, sweet potatoes, and barley.
- Lignocellulose biomass, which includes wood, straw, and grasses.

Bio-ethanol production mainly relies on sucrose-containing feedstock and starchy materials. However, in the long term, lignocellulose biomass has the potential to provide a significant portion of the raw materials for bio-ethanol production due to its low cost and abundance.

To ensure the production of ethanol that provides greenhouse gas (GHG) benefits, several requirements need to be met. Firstly, ethanol plants should prioritize the use of biomass over petroleum fuels. This shift towards biomass helps reduce GHG emissions associated with ethanol production. Secondly, it's essential to avoid cultivating annual feedstock crops on land rich in carbon. Doing so helps preserve carbon-rich soils, preventing further release of greenhouse gases into the atmosphere. Thirdly, it's crucial to effectively utilize by-products generated during ethanol production to maximize energy output. Efficient utilization of by-products contributes to overall energy efficiency and reduces waste. Lastly, efforts should be made to minimize nitrous oxide emissions through the adoption of efficient fertilization methods. By implementing these measures, the ethanol production process can significantly contribute to reducing greenhouse gas emissions and promoting environmental sustainability.

d) Bioethanol Economy

Cost plays a vital role in the research and consumption of any fuel. It must be competitive, especially when compared to fossil fuels. This competitiveness ensures a market for biofuels, as people will see the benefits of converting to a renewable energy source. Therefore, cost optimization must also be considered when analyzing crop rotations.

Initially, bio-ethanol was considerably more expensive than gasoline fuels, but governments took efforts and implemented policies to encourage its production and consumption. Mainly, three approaches were followed to support bio-ethanol:

- Policies based on taxation.
- Policies based on agriculture subsidies.
- Fuel mandates.

Recently, rather than focusing solely on the energy sector, the promotion of biofuels is mainly carried out through the agricultural sector and green lobbies. Most biofuel programs depend on subsidies and government policies, which pose a market risk and can be costly for governments. However, it can become cost-effective through the steady progression of technology development, especially when oil prices are high, and the undesirability of fossil fuels grows each year.

Estimates of the costs of bio-ethanol production from different feedstocks are provided in the following table.

	2006	Long-term about 2030
Price of oil, US$/barrel	50–80	
Corresponding pre-tax price of petroleum products, US cents/l	35–60[a]	
Corresponding price of petroleum products with taxes included,	150–200 in EU[b]	
US cents/l (retail price)	About 80 in USA	
Bio-ethanol from sugar cane	25–50	25–35
Bio-ethanol from corn	60–80	35–55
Bio-ethanol from beet	60–80	40–60
Bio-ethanol from wheat	70–95	45–65
Bio-ethanol from lignocellulose	80–110	25–65

[a] Note range differs from row 1, for several factors such as refinery costs.
[b] Excluding a few outliers above and below this range.

Figure 2: Comparison of Production cost | Source [14]

60-70% of the production cost is attributed to feedstock. Production costs from sugar/starch-containing crops are unlikely to decrease significantly further as they have already reached maturity. Research has also concluded that the production costs of bio-diesel are generally lower than those of bio-ethanol.

e) Limitations on Bioethanol Production

Biofuels have demonstrated numerous advantages and possess many attractive characteristics, which have garnered strong support from governments worldwide. However, they also come with several disadvantages that may jeopardize their future existence. The following is a list of some of their characteristic limitations:

- Low energy density compared to gasoline.
- Corrosive effects on mechanical parts.
- Very low luminosity in its flame.
- Issues with cold start due to low vapor pressure.
- Miscibility with water.
- A certain level of toxicity to the environment.

Bio-ethanol production generally utilizes residuals from food crops such as corn grain and sugar cane. The limited supply of these crops can lead to competition between their use in bio-ethanol production and food provision. Corn-based bio-ethanol production is minimal in most of the countries assessed, especially when compared to the United States. This production process generates a significant amount of waste, posing environmental hazards. The cultivation of raw materials involves various disadvantages, including the depletion of water resources, land requirements, and soil mineral exhaustion due to continuous farming on the same land.

1.2 Hydrogen

Sustainable energy is driven by global needs to reduce CO2 emissions, improve air quality, ensure energy supply security, and develop a new industrial and technological energy base, all crucial for economic prosperity and our future vision. Hydrogen presents a compelling alternative to fossil fuels for several reasons. One reason is its ability to be produced from numerous resources, including both renewable and non-renewable sources. We can utilize hydrogen in high-efficiency power generation systems, such as fuel cells, for transportation and electricity distribution. In hydrogen vehicles, fuel cells convert hydrogen and an oxidant directly into electricity through a low-temperature electrochemical process, which can then power the vehicle's electric motor.

a) Trends

Fuel cells, which operate on hydrogen or hydrogen-rich fuels, have the potential to become major catalysts in transitioning to a future sustainable energy system with low CO2 emissions. This importance is rapidly increasing as developments in this area are closely tied to such progress. Many countries have set targets and planned accordingly to leverage fuel cell and hydrogen technologies. European countries, for instance, have plans to develop hydrogen and fuel cell technologies, aiming for 1 GW of distributed power generation capacity using fuel cells by 2015 and sales of 1.8 million hydrogen vehicles per year by 2020.

Currently, three major technological problems must be addressed to transition from a carbon-based energy system to a hydrogen-based economy. First, costs must be reduced for efficient and sustainable hydrogen production and delivery. Second, new generations of hydrogen storage systems must be developed for both vehicular and non-vehicular applications. Finally, the price for fuel cells and hydrogen systems must be reduced. In this future integrated energy system, it is likely that both small and large fuel cells will be combined to generate electricity using local hydrogen resources.

It is important to stress that hydrogen is not actually a primary source of energy, as is the case with coal, oil, or gas. Its role is more akin to that of an 'energy carrier,' produced using energy from other sources and capable of being transported for future use, where its stored energy can be converted to the desired form. Hydrogen can be stored as a fuel and utilized for transportation purposes using fuel cells or internal combustion turbines, leaving only water and no CO2 in the exhaust.

Another important feature of hydrogen is its potential use as a storage medium for electricity generated from renewable resources such as wind, tidal, and solar power, making it a solution for sustainable energy. If hydrogen is produced from non-fossil fuels, it can be considered a sustainable fuel. Moreover, locally produced hydrogen has successfully facilitated the integration of renewable energy into the transportation sector, offering significant economic benefits and enhancing energy security. The energy storage capacity

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of hydrogen is a crucial element that bridges sustainable energy technologies with a sustainable energy economy, often referred to as the 'hydrogen economy'.

Maintaining the safety of hydrogen is complex, involving not only scientific and technological aspects but also the psychological attitude of consumers toward it. Despite its reputation, hydrogen has demonstrated extraordinary safety benchmarks during many years of use in industrial applications. However, hydrogen is significantly different from traditional fuels due to its distinct combustion properties compared to carbon-containing fuels. These differences require unique safety precautions and the development of a suitable operational culture, particularly in situations where customers will interact directly with hydrogen and fuel cell technologies.

b) Hydrogen Production, Distribution & Storage

While hydrogen is abundantly available, it exists primarily in the form of chemical compounds, necessitating its production from hydrogen-containing sources. Hydrogen can be derived from various sources, including coal, natural gas, biomass, hydrocarbons, and even municipal waste, using a variety of techniques. This diversity ensures the security of fuel supply. Hydrogen is primarily produced through steam reforming of hydrocarbons, typically methane. Catalytic steam reforming is employed for light hydrocarbons such as methane and naphtha. The process involves three stages of hydrocarbon treatment: generation of synthesis gas, shift reaction reforming, and gas purification. However, CO2 sequestration has not yet been technically and commercially proven.

Another promising method is high-temperature pyrolysis of biomass, municipal solid waste, and hydrocarbons. Currently, the cost of this process exceeds that of steam reforming of natural gas. Additionally, hydrogen can be produced by splitting water through various processes, including electrolysis, high-temperature decomposition, photo-electrolysis, and photo-biological water splitting.

Commercial generation of hydrogen by water electrolysis achieves an efficiency of about 70–75%. However, the cost of hydrogen produced by this method is several times higher than that produced from fossil fuels. While renewable sources of energy may provide local sources of hydrogen, they are unlikely to meet the large volumes of hydrogen required for global energy needs.

At present, methods for transporting and distributing hydrogen include compressed gas in tube cylinders, liquid hydrogen tanks, and networks of hydrogen pipelines. These methods significantly contribute to the cost of hydrogen for end-users. In some cases, decentralized local hydrogen production through methane reforming or electrolysis of water may prove to be more feasible.

One of the important technological barriers to the widespread use of hydrogen as an effective energy carrier is the lack of a safe, lightweight, and low-cost hydrogen storage method with high energy density. Hydrogen has a higher energy-to-weight ratio than other fuels commonly used.

Current storage options for hydrogen primarily focus on high-pressure gas containers or cryogenically cooled liquid hydrogen. However, one disadvantage of these methods is the significant energy penalty they incur. Approximately 20% of the energy content of hydrogen is needed to compress the gas, and up to 40% is required for liquefaction. Additionally, public perception and acceptability associated with the use of pressurized gas and liquid hydrogen containment present another barrier. Achieving breakthroughs in hydrogen storage is crucial to overcoming these challenges. It is widely recognized that finding the most acceptable alternative to compressed and liquid hydrogen will require significant scientific and technological advancements.

c) Fuel Cells

Fuel cells have emerged as a leading alternative technology compared to polluting internal combustion engines and stationary distributed energy applications. Moreover, they are poised to improve the capabilities of battery technology due to increased demand for portable electric power supply in the future. A fuel cell is a device that continuously recharges batteries and produces electricity through the electrochemical reaction of hydrogen and oxygen present in the air. This reaction occurs at low temperatures. The main difference compared to battery storage is that fuel cells can produce electricity continuously as long as gas fuel and air are supplied. Various types of fuel cells can utilize any hydrogen-rich fuel by employing either an external or internal fuel-reforming process. However, the use of hydrocarbon-based fuels will result in CO2 emissions.

Fuel	Specific energy (kWh/kg)	Energy density (kWh/dm^3)
Liquid hydrogen	33.3	2.37
Hydrogen (200 bar)	33.3	0.53
Liquid natural gas	13.9	5.6
Natural gas (200 bar)	13.9	2.3
Petrol	12.8	9.5
Diesel	12.6	10.6
Coal	8.2	7.6
NH_3BH_3	6.5	5.5
Methanol	5.5	4.4
Wood	4.2	3.0
Electricity (Li-ion battery)	0.55	1.69

Figure 3: Energy Density for Vehicle Fuels | Source [18]

Hydrogen-powered fuel cells emit water and produce almost no pollutant emissions, including nitrogen oxides, as they operate at much lower temperatures than internal combustion engines (IC engines). However, even fuel cells fueled by hydrocarbon fuels have the potential to supply efficient, clean, and quiet energy conversion, contributing to a significant reduction in greenhouse gases and local pollution. Unlike IC engines, fuel cells are not bound by the limitations of the Carnot cycle, allowing them to convert fuel into electricity at more than twice the efficiency. Hydrogen fuel cell engines can operate at up to 65% efficiency, compared to just 25% for present-day IC engine vehicles. When the heat generated in fuel cells is utilized in combined heat and power systems, the overall efficiency can exceed 85%.

Fuel cells are classified based on the nature of their electrolyte, which also determines their operating temperature, the type of fuel, and a range of applications. The electrolyte can be an acid, base, or salt. Low-temperature proton exchange membrane fuel cells (PEMFCs) and alkaline

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fuel cells provide an order of magnitude higher power density than any other fuel cell systems. However, they have a major disadvantage as they require costly platinum catalysts and very pure hydrogen. PEMFCs are favored for mass-market automotive and small-scale combined heat and power (CHP) applications, and there is a massive global effort to develop commercial systems. The image below shows a schematic of a fuel cell.

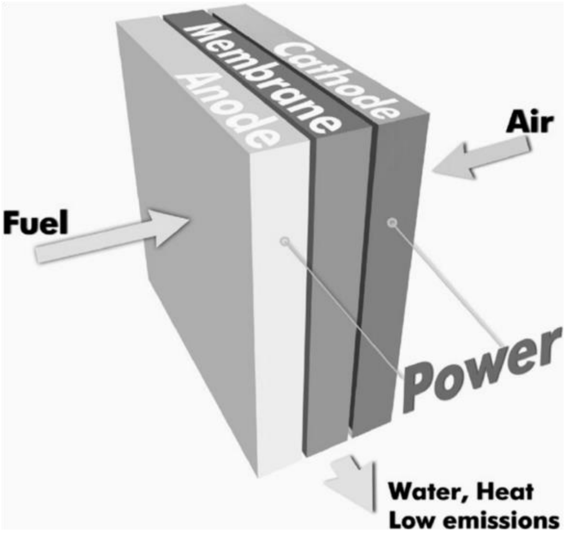

Figure 4: Schematic representation of a Fuel cell | Source [18]

By 2050, the global demand for energy could double or triple, surpassing the capabilities of petroleum and natural gas to meet these requirements. Hydrogen and fuel cells are being considered in many countries as important fuel alternatives and key technologies for future sustainable energy systems. However, the transition of the economy towards hydrogen will be a lengthy process. The timeline for this transition will also depend on decisions made by leading countries such as the USA, Japan, Canada, and Europe. For instance, the European Commission is supporting hydrogen theory and fuel cell technology platforms by allocating €2.8 billion over a period of 10 years. During this transition, it will be crucial to develop advanced and clean processes, reduce CO2 emissions, and create new, efficient, and low-cost electrolyzers. Additionally, hydrogen will need to become commercially competitive with fossil fuels. To achieve this, developed and sustainable hydrogen storage technologies, along with viable transportation mediums, will be required.

1.3 Natural Gas Vehicle

a) Market Benefits and Reserve

Natural gas is emerging as one of the most potential alternative fuels today, as illustrated by the graph below. The proven gas reserves over the past few decades and their rapid growth have become increasingly significant politically and scientifically. The world's proven reserves are estimated to be around 187 trillion cubic meters, with Russia alone possessing 47 trillion cubic meters of reserves. These figures are increasing at a rapid pace every year, driving the development of technologies for such alternative fuels.

A natural gas vehicle (NGV) utilizes compressed natural gas (CNG) or liquefied natural gas (LNG), which proves to be cleaner for the environment compared to fossil fuels. By 2011, there were 14.8 million vehicles based on NGV technology worldwide. Among them, 2.86 million were in Iran, 2.58 million in Pakistan, 2.07 million in Argentina, 1.70 million in Brazil, and 1.10 million in India. The Asia-Pacific region has the highest number of natural gas vehicles in the world, with 6.8 million vehicles, followed by Latin America, with 4.2 million vehicles. Almost 90% of these vehicles in Latin America are equipped with bi-fuel engines, allowing them to run on either gasoline or CNG. Nearly every vehicle in Pakistan has been converted to use alternative fuel, while still retaining the ability to run on gasoline. By 2009, the United States had 114,270 compressed natural gas (CNG) vehicles, the majority of which were buses, while there were 147,030 vehicles running on liquefied petroleum gas (LPG) and liquefied natural gas (LNG), totaling 3,176 vehicles.

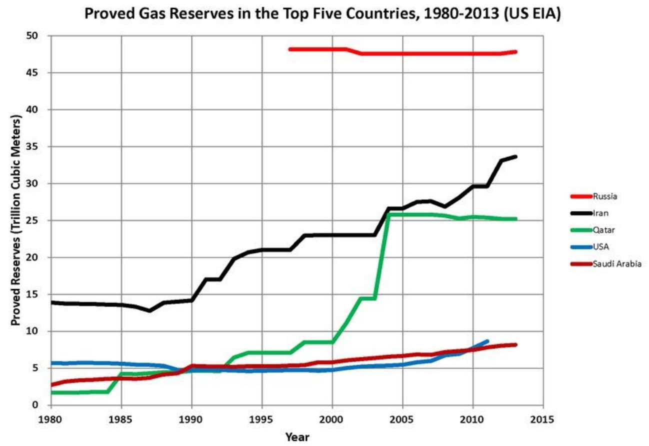

Figure 5: Source [19]

India, Australia, Argentina, and Germany are among the countries where natural gas-powered buses are popular. In 2010, Pakistan had the highest market share of NGVs at 61.1%, followed by Armenia at 32%, and Bolivia at 20%. The number of NGV refueling stations worldwide was around 18,202 by 2010. Heavy vehicles with diesel engines can also be converted to NGVs, using natural gas as the primary fuel and a small amount of diesel fuel for ignition.

An increasing number of vehicles worldwide are being produced to run on compressed natural gas (CNG). The Honda Civic GX was one of the first NGVs commercially available in the US market. However, Ford, GM, and Ram now offer bi-fuel models in their vehicle lineups. Currently, Ram is the only manufacturer that produces a pickup truck with a factory-installed bi-fuel system in the US market; others provide kits that are installed outside the company. NGV filling stations can be located wherever natural gas lines exist. While liquefied natural gas (LNG) stations are typically built on a larger scale, CNG stations can be smaller. Fuel maker Company pioneered a system called Phill Home Refueling Appliance, developed in partnership with Honda for the American GX model.

b) Limitations

Despite its advantages, there are also several disadvantages of this system:

- CNG needs to be stored in high-pressure cylinders (operating at pressures of 3000 psi to 3600 psi), while LNG requires cryogenic cylinders (operating at temperatures between -260°F to -200°F).

- These cylinders occupy more space than gasoline or diesel tanks, necessitating intricate shaping to store more fuel while using less on-vehicle space.
- CNG tanks are typically placed in the boot or trunk of the vehicle, reducing available storage space. However, this can be mitigated by installing tanks under the body of the vehicle.
- Another significant disadvantage is the lack of infrastructure. Gas distribution networks are not widely spread worldwide.

1.4 Hybrid Vehicles (HEV) & Plug-in Hybrid Vehicles (Phev)

Hybrids are utilized to maximize the efficiency of vehicles, mitigating both the shortcomings and benefits of electric vehicles. Commonly, hybrid vehicles are designed to offset the disadvantages of both electric and internal combustion (IC) engines. The most common type of hybrid vehicle is the gasoline-electric hybrid, which utilizes gasoline for the IC engine and electric batteries to power electric motors. These motors are typically smaller and may be considered underpowered; however, they can provide a satisfactory driving experience, especially when combined with IC engines during acceleration.

Plug-in hybrid electric vehicles (PHEVs) primarily rely on large-sized batteries as their primary energy source, with the IC engine providing support to the electric motor when needed. Range is a significant concern for PHEVs, as battery capacities may not meet desired distances. In such cases, IC engines can supplement the power requirements of these vehicles.

The main differences between Hybrid and Plug-In hybrid vehicles can be understood from the following two main points:

Hybrid:

- Gasoline-powered IC engines are the main source of propulsion.
- Electric motors are used to complement the IC engine.
- Electricity is generated on board.
- Energy savings are typically less substantial compared to Plug-In Hybrid Electric Vehicles (PHEVs).

Plug-in Hybrid:

- The main source of power is the battery-powered electric motor.
- The IC engine is used to complement the electric motor and extend the range.
- Electricity is supplied from the grid.
- Energy savings are typically greater in Plug-In Hybrid Electric Vehicles (PHEVs) compared to Hybrid Vehicles.

The Toyota Prius is a highly successful hybrid vehicle, first sold in Japan in 1997 and available worldwide by 2000. Japan and the USA have been particularly successful markets for the Prius. By 2013, Toyota had sold almost 3 million units worldwide. Other companies such as Honda and GM have also sold many hybrid vehicles since then. By 2013, around 7.5 million hybrid electric vehicles had been sold worldwide, comprising approximately 50 models from various manufacturers.

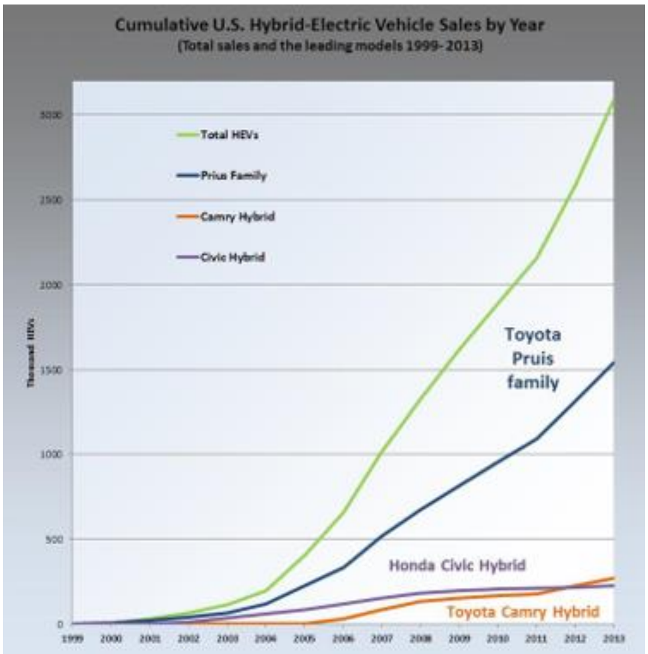

Figure 6: Source [25]

2. Conclusion

Alternative vehicle fuels are undoubtedly the way forward in ensuring a sustainable and environmentally friendly transportation sector. As highlighted in this paper, the journey towards widespread adoption of these fuels is not without its challenges. However, with increasing research and development in this field, it is hoped that solutions to these challenges will emerge, making these fuel options as widely used as, if not more than, petroleum.

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