A Comparative Analysis of Alternative Energy Sources Used in Automobiles

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Abstract: Due to the rapid decline of oil reserves and the environmental regulations that lower the limit values of exhaust emissions released into the atmosphere the car makers and the scientific communities have been accelerating their studies on the use of alternative energy sources in automobiles. To determine which alternative energy source is suitable for automobiles in terms of the existing conditions is a very important issue. It is necessary to know the characteristics of these energy types and evaluate their advantages and disadvantages to make this determination. In this study, a comparative analysis is performed for fuels such as LPG, CNG, hydrogen, biodiesel, ethanol and methanol, which could be used as an alternative to gasoline and diesel, and electric, hybrid and fuel cell vehicles. According to the comparison, LPG and CNG seem to be best alternative fuels for economical reasons, while electric and fuel cell vehicles stand out as their emission advantages.

Keywords: LPG, CNG, hydrogen, alcohol fuels, EV, HEV, FCV

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1. INTRODUCTION

Factors such as increasing world population, economic growth and rise of per capita energy consumption, induce energy amount used in the world with each passing day. This increase in energy consumption raises two major problems; increasing energy prices due to the limitations of energy sources, and environmental pollution caused by intensive energy use [1]. A large part of the energy consumed on the world is spent by motor vehicles, which are operated mostly with gasoline and diesel fuel derived from crude oil that is a form of energy with limited reserves [2]. Together with the limited resources, the constantly increasing energy needs, which may cause difficulties for all over the world in the future, is a problem to be solved [3].

Another problem arising due to the increase of energy consumption is the environmental pollution. One of the most important factors of environmental pollution is motor vehicles. As a result of conducted researches, it is known that air pollution in major cities in the world due to motor vehicles reach 50% of total air pollution [4, 5]. Carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matter (PM) emissions, which are come out by motor vehicles burning hydrocarbon fuels, constitute serious health problems polluting the atmosphere. Motor vehicles are responsible not only for toxic emissions like HC, CO, NO_x and PM, but also carbon dioxide (CO_2) that causes the greenhouse effect.

An alternative fuel, which is seen as a necessity according to the afore mentioned reasons, should be technically feasible, economically competitive with conventional fuels, environmentally safe and easily obtainable [6]. It is clear that more features of these a fuel provides, more alternative it will be. In this study, LPG, CNG, biodiesel, alcohol fuels and hydrogen that are used as alternatives to conventional fuels in the internal combustion engines and electric, hybrid and fuel cell automobiles are to be examined; some of their important features comparatively analyzed.

2. PROPULSION METHODS OF AUTOMOBILES

In today's vehicles, there are two different engine options powered by conventional fuels and applications are developed to work with on alternative energy sources. The first of these is internal combustion engines, and the other is electric motors. In internal combustion engines, fuel is burned within the cylinder resulting pressure rise and the piston inside the cylinder is pushed rapidly. This linear movement of the piston is converted into a circular motion through the connecting rod-crank mechanism. And via a flywheel connected to the crankshaft, this circular motion is transmitted to the wheels being arranged by a clutch, gearbox and differential system. As for electric motors, they provide rotational movement directly when their electrification starts. Electric motors are often attached directly to the wheels and so they don't have a gearbox and differential as a power train.

Internal combustion engines are mostly manufactured in two ways as "spark ignition" (SI) and "compression ignition" (CI). SI engines work according to the Otto cycle, CI engines work according to the Diesel cycle. There are some fundamental differences between Otto and Diesel cycles. These differences are indicated in Table 1.

Table 1 Some differences of Otto and Diesel cycles

	Otto cycle	Diesel cycle
Fuel	Gasoline	Diesel
Suction stroke	Air + fuel mixture is taken	Only air is taken
Compression Ratio	7/1 – 14/1	14/1 – 24/1
Ignition	With spark plug	With fuel injection

In internal combustion engines, not only gasoline or diesel is burned, but fuels like LPG, CNG, ethanol, methanol, biodiesel and hydrogen can be utilized as well. Regarding some engines that are called flexible fuel engines, the mixture of two or more fuels can be used. Engines that use gasoline-ethanol blends, gasoline-methanol blends or diesel-biodiesel blends are examples of flexible fuel engines. Many vehicles, currently available in the market, are able to work with similar fuel mixtures without the need of any modifications. Some of the types of fuels can be used in which type of engine systems are in Table 2 below [7].

Table 2 Types of engine, fuel, and fuel system

Fuel	Engine	Fuel System
Gasoline	SI	mono
Diesel	CI	mono
LPG	SI	mono, bi-fuel
CNG	CI, SI	mono, bi-fuel
Hydrogen	SI, FC	mono, bi-fuel
Ethanol	SI, CI, FC	mono, ffv
Methanol	SI, CI, FC	mono, ffv
Biodiesel	CI	mono, ffv

SI : Spark Ignition
CI : Compression Ignition
FC : Fuel Cell
mono : only one type of fuel
bi-fuel : more than one type of fuel without mixing
ffv : fuel blends

Compared to the internal combustion engines, electric motors have a simpler construction with respect to the movement generation and transmitting it directly to the wheels. Electric motors work basically with the principle of "a conductor located in a magnetic field moves when energized". The energy needed for the electric motors is provided in various ways. The most important of them are as follows:

- A battery group charged from the outlet,
- A battery group charged by an internal combustion engine that works as a generator,
- Fuel cell system.

On the other hand, the battery can be charged by some different methods as in hybrid systems, which convert kinetic energy of the vehicle into electricity during braking, or solar systems, which generate power from the sun, as well. The method of electric production varies according to the country's conditions in systems charged from the outlet. The production cost and the environmental impact are varied according to the production sources of electricity such as wind, water, the sun, nuclear, coal, petroleum, or natural gas. By the way, fuel systems of internal combustion engines are gaining importance in the systems that the engine works as a generator and charges the battery. The engine can be operated with conventional fuels like gasoline and diesel or alternative fuels. In the fuel cell system, electricity is produced through a chemical reaction between hydrogen and oxygen. In these systems, only water vapor and unused air emerges as emissions. The necessary hydrogen can be produced on the vehicle or is used from the tank.

3. ALTERNATIVE ENERGY SOURCES FOR AUTOMOBILES

Today, the vast majority of the energy used is met from fossil fuels (petroleum products, coal, etc.). In general, searching for alternatives for energy sources continues unabated for three reasons:

- Rapid reduction of fossil fuel reserves and their end in the future (excessive rise in energy prices due to the bottleneck)
- Environmental effects (toxic gases and CO_2 that causes the greenhouse effect)
- Demands of countries to diversify their energy sources and get rid of external dependence.

A variety of alternative energy sources are used in order to mobilize vehicles. LPG, CNG, ethanol, methanol, biodiesel, hydrogen, fuel cells and electricity are some of these energy sources. Various factors are outstanding for one or more of these fuels are often used in different parts of the world. The most important factor has been the cost. In some countries however, the use of alternative fuels is encouraged as a legal obligation due to environmental reasons.

Although there are some positive aspects of alternative fuels, there are also negatives. Some of them are storage challenges and costs, high initial purchase costs, the conversion costs, less availability of filling stations, longer fuel filling time and low vehicle range. Thanks to works done to overcome these negative aspects, the situation is much better than before, and it is a reality that alternative fuels will be used on a large scale over the world in the future.

3.1. Liquefied Petroleum Gas (LPG)

LPG, mainly consisting propane, butane, or a combination of them as a mixture in different ratios, is a colorless, odorless gas. Some important characteristics of propane and butane are shown in Table 3.

In the world in general, for LPG use as a fuel in automobiles, rather than the production of vehicles powered by LPG in factory, vehicles are converted to LPG after sales in LPG conversion workshops. LPG conversion of automobiles is accomplished by the addition of only some specific parts into the vehicle system. This process takes several hours. The car's current fuel and ignition systems are being preserved intact, and fuel switching is provided through a fuel selector switch placed in the cab. Today, many car manufacturers offer to their customers both gasoline and LPG powered cars as an option.

Table 3 Characteristics of propane and butane [8]

Properties	Propane	Butane
Chemical formula	C_3H_8	C_4H_{10}
Volumetric mass at 15 °C (kg/ dm^3)	0.508	0.584
Vapor pressure at 37,8 °C (bar)	12.1	2.6
Boiling temperature (°C)	-42	-0.5
R.O.N.	111	103
M.O.N.	97	89
The lower heating value (kJ/ kg)	46100	45500
The lower heating value (kJ/ dm^3)	23400	26500
Liquid phase specific heat (kJ/ kg °C)	1366	1276

Compared with the conventional fuels, some important advantages and disadvantages of LPG can be summarized as follows [8, 9]:

+ LPG is a cheaper fuel (47% than gasoline, 44% than diesel on average).
+ LPG, having a higher octane number, inhibits the formation of detonation and allows the engine high compression ratios. However, because the compression ratio is determined by the initial design for gasoline in dual fuel (gasoline \ LPG) vehicles, a higher compression ratio can be achieved with engine modification only for this type of vehicles [10].
+ LPG conversion system consists of simple and inexpensive parts.
+ LPG, which enters into the combustion chamber in the gas phase completely, does not cause the dilution of the engine oil leaving no residue. Thus it leads to lower maintenance costs compared to gasoline [9].
+ Gaseous fuels are hydrogen-rich and enter into the cylinders in the gas phase. These two characteristics provide a clean combustion. Vehicles using LPG emit approximately 60% lower CO, 20% lower HC and 30% lower NO_x emissions compared with diesel and gasoline fueled vehicles [9, 11-19].
+ Combustion products have adverse effects on atmosphere. However, each compound's toxicity and the actual degree of harmfulness are more important than the absolute amount of substances [8]. As we can see in Table 4, LPG does not have sulfur dioxide and aldehydes that are the most toxic products of the combustion [8].

Table 4 Toxicity parameters of exhaust gases

Compound	Toxicity parameter
Carbon monoxide (CO)	1
Hydrocarbon (HC)	60
Nitrogen oxides (NO_x)	100
Aldehyde	130
Sulfur dioxide	130

+ LPG has reached sufficient numbers in terms of filling stations in many countries.

– LPG has a lower heating value than gasoline, and this causes about 2-3% power reduction in engines.

– A certain cost is required for the conversion of vehicles to LPG.

– LPG system is usually in need of gasoline working of engine to heat the coolant of the engine, in cold start.

– Exhaust emissions and fuel consumption is increasing in faulty installation of the LPG system.

– Since LPG is a flammable and explosive gas, it poses a danger in accidents, albeit low.

3.2. Compressed Natural Gas (CNG)

Natural gas is a colorless, odorless gas and it is lighter than air. Methane (CH_4) poses the largest weight in the chemical composition of natural gas. Combustion efficiency of CH_4 is very high thanks to its simple carbon structure. Physical and chemical properties of a dry and clean natural gas (methane) are shown in Table 5 [7].

Table 5 Physical and chemical characteristics of methane

Properties	Methane
Chemical formula	CH_4
Molecular weight (kg/kmol)	16.04
Density (kg/m^3)	0.65-0.80
Higher heating value (kJ/kg)	38330
Lower heating value (kJ/kg)	34541
Flammability range (air/fuel %)	5-15
Boiling point (°C)	-161.5
Octane number	125

Vehicles powered by natural gas, are called as NGVs (Natural Gas Vehicle) briefly. More than 15 million vehicles worldwide are known to operate with natural gas. Vehicles may be manufactured in the factory directly to operate with natural gas. However in general, they work with a systematic called "Bi-Fuel", which requires a number of modifications to the gasoline engine, using only one fuel at a time, but having an infrastructure of two different fuels for engine working. This application is similar to the method of implementation of LPG system on gasoline powered vehicles. As for diesel vehicles, there are two different situations for CNG usage. The first application is performed in a diesel engine with a number of serious modifications and the engine quits diesel fuel and is adapted to work with only natural gas. The latter is the application called "Dual-Fuel", which uses diesel fuel and natural gas mixture in certain ratios as a fuel. In this application, while the first run of engine performed by diesel fuel, when a certain speed (1500-2300 r/min) of the engine is exceeded, the engine starts to run on natural gas [7].

By using natural gas as a vehicle fuel, following advantages and disadvantages are obtained [7]:

+ The consumption cost of natural gas is very low in comparison with the other fuels.

+ Natural gas is one of the least polluting fuels. Exhaust emissions from the combustion of natural gas are far below the "Ultra Low Emission Vehicle" (ULEV) standards. Particulate emissions emitted from the CNG vehicles are better than diesel or dual fuel engines [20]. It becomes possible to reduce NO_x emissions by 90% and CO emissions by 25% with the use of natural gas. Due to the low carbon content of natural gas (Figure 1), CO_2 emissions decrease by up to 25%.

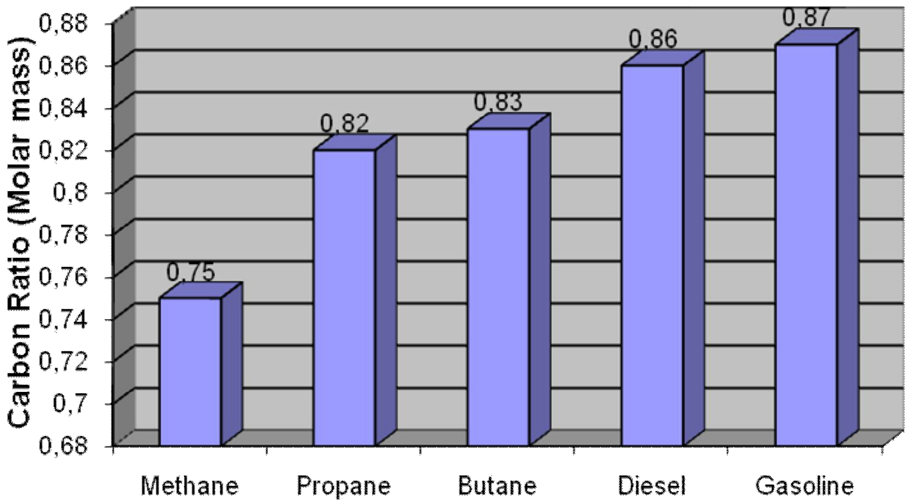

Fig. 1 Carbon ratio of methane, propane, butane, diesel and gasoline [21]

+ Since natural gas has a high octane number, thermal efficiency of an engine powered by natural gas can be 10% higher than a gasoline engine.

+ Compared with other fuels, combustion of natural gas in engines gives a 30% decrease in noise emissions.

+ Thanks to its simple chemical structure, CNG establishes a clean combustion in engines. Thus, vehicle engine would be less worn and a significant amount of maintenance savings achieved.

+ Because CNG is lighter than air, it rises instantly in the presence of any leaks. Also due to a high ignition temperature and a wide range of flammability, the likelihood of any fire diminishes at an accident.

– CNG has lower energy content at gaseous phase. Because of this property, it is usually stored as compressed at the range of 200-250 bar pressure in vehicles. For this reason, a CNG fuel tank takes 4-5 times more volume requirements than a gasoline or diesel tank in order to carry the same amount of energy. This means again 4-5 times more weight will be on the vehicle in the case of steel used as a tank material. If composite CNG tanks are used, the problems arising from the weight (fuel consumption, range, etc.) would decrease. However, the use of such materials naturally increases the cost of these tanks.

– CNG filled into the tank at high pressure extends the filling time.

– As the use of compression method is more efficient and more common to store natural gas, it may also be stored in liquid form and then used in vehicles. However, this practice requires a very low liquid temperature as -161.5 °C at atmospheric pressure. A fuel tank to be used for liquefied natural gas (LNG) is much smaller than a CNG fuel tank. But maintaining the gas at very low temperatures requires very well-isolated tools, and it takes a considerable increase in costs.

3.3. Biodiesel

Biodiesel is an alternative fuel that can be produced from renewable sources such as vegetable and animal oils for diesel engines [22]. Vegetable oils are derived generally from canola, soybean, nuts, sunflower, cotton, and corn [23, 24]. These oils undergo various processes being reacted with a mixture of an appropriate alcohol (ethanol or methanol) and a catalyst (sodium hydroxide or potassium hydroxide), and biodiesel and glycerin are obtained as products [7]. In Table 6, physical and chemical properties of the biodiesel fuels obtained from commonly used plant oils in the production of biodiesel is shown [25].

Table 6 Properties of diesel and biodiesel obtained from some plants

Fuels	Energy content (kJ/kg)	Density (kg/dm³)	Viscosity (mm²/s)		Cetane number	Flash point (°C)	Chemical formula
			27 °C	75 °C			
Diesel	43350	0.815	4.3	1.5	47	58	$C_{16}H_{43}$
Sunflower	40560	0.878	10	7.5	45-52	85	$C_{55}H_{105}O_6$
Cotton	40580	0.874	11	7.2	45-52	70	$C_{54}H_{101}O_6$
Soybean	39760	0.872	11	4.3	37	69	$C_{53}H_{101}O_6$
Corn	37830	0.915	46	10.5	37.6	270-295	$C_{55}H_{103}O_6$

Biodiesel is used in diesel engines mixing with diesel fuel at low or high ratios. When the proportion of biodiesel is low, no technical changes are made in the engine. At high rates of biodiesel or completely biodiesel usage, the engine is made prepared with some changes to use biodiesel. On the other hand, it is mandated by many countries that diesel fuel has to consist a certain percentage of biodiesel by law. For example, in Turkey, being valid from 2014, every liters of diesel fuel purchased from stations have to include 1% vegetable oil.

Advantages and disadvantages of biodiesel can be listed as follows [7, 23, 25, 26-29]:

+ Biodiesel is produced from agricultural waste and produce of it is easy.
+ Biodiesel can be mixed in different proportions with diesel fuel.
+ Biodiesel can be used without any changes on the engine.
+ The exhaust gas is less toxic and smells better when biodiesel is used as pure or in mixture.
+ Harmful gases emitted into the environment by the combustion of biodiesel contain 15% less CO, 78% less CO_2, 27% less HC, 22% fewer particulates and 50% less soot according to diesel fuel. It also does not contain toxic waste and does not harm the nature (occurring no sulfur oxide (SO_X) and reducing toxic polycyclic aromatic hydrocarbons (PAH) by 80%).
+ Sulfur compounds that cause acid rain is almost absent in biodiesel fuel.
+ Biodiesel does not have any toxic effects against aquatic life. On the contrary, 1 liter of crude oil may cause contamination of 1 million liters drinking water.
+ Since biodiesel has a good lubrication quality, engine wear decreases.
+ The flash point of the biodiesel is higher (> 110 °C) than the diesel fuel. This feature of biodiesel ensures it a safer fuel to use, transport, and store.

+ Since the cetane number of biodiesel is higher than that of diesel, ignition delay becomes shorter and the engine works with less knocking [30].

– The energy content of biodiesel is 8% lower than diesel giving 5% loss of efficiency.

– Due to its lower energy content, biodiesel fuel tanks must be bigger than that of diesel about 15% by weight, and 9% by volume for the same vehicle range.

– Inadequate cultivation in agricultural sector and taxes cause biodiesel to be expensive compared to diesel.

– While the flaking temperature of diesel is -7°C, it is +3°C for biodiesel. At these temperatures, the fuel becomes gel form by clogging filters leading to the congestion of fuel flow.

– Fuel consumption increases with the use of biodiesel.

– High viscosity of vegetable oils causes the growth of droplet size during injection of the biodiesel into the cylinder, and this hinders the complete of combustion. In case of incomplete combustion, accumulations in the combustion chamber, unburned fuel entering the engine lubricating oil and the collecting here to dilute of the engine oil and coking of injectors occur. For the solution of this viscosity problem, biodiesel fuel is mixed with diesel fuel in certain proportions.

– Residues of biodiesel combustion create frequent filter changes and the tank cleaning time intervals.

3.4. Ethanol

Ethanol or ethyl alcohol (C_2H_5OH) is a type of an alcohol derived from the fermentation of sugar and substances that can be converted to sugar like cellulose or starch. Ethanol also can be obtained from agricultural products such as potatoes, cereals, sugar cane and sugar beet [31]. Properties of ethanol are seen in Table 7.

Table 7 Properties of ethanol

Properties	Ethanol
Formula	C_2H_5OH
C/H ratio	0.333
Molecular weight (kg/kmol)	46
Lower heating value (kJ/kg)	26.900
RON	106
MON	89
Heat of vaporization (kJ/kg)	921.1
Freezing point (°C)	-118
Boiling point (°C)	78
Density (kg/m^3)	794

Ethanol is used as an alternative energy source for automobiles in many countries, especially in Brazil. Most of the automobile manufacturers produce yellow tank covers for vehicles using ethanol-gasoline blend [32, 33]. Also, the percentage of ethanol in gasoline is expressed by abbreviations such as E10, E25, E100 on tank covers of vehicles and pumps of filling stations. On the other hand, in some countries like Turkey, it is mandatory that every liter of gasoline has to include a certain rate (2-3%) of ethanol in every station over the country [34]. In spark ignition engines, ethanol is used alone or participating to gasoline in specific proportions. In diesel engines, however, ethanol can be used only with diesel fuel at some proportions and in case of using a spark plug [7].

Using ethanol in automobiles as a fuel several advantages and disadvantages are provided. Some of these are given below:

+ Since the heat of evaporation, the octane number and the self-ignition temperature of ethanol is high enough, it can be used in high compression ratio in engines; resulting increase of the engine power, and decrease of the specific fuel consumption [35-39].
+ With a high heat of vaporization, ethanol creates a cooling effect on the fresh mixture absorbing heat when evaporates, and this increases the volumetric efficiency of the engine.
+ When the ethanol amount increases in the mixture, CO, HC and CO_2 emissions are reduced [37, 40-43].
+ Ethanol raises the knock resistance of the engine [44].
+ Fire hazard of ethanol is lower than gasoline.
– Specific fuel consumption of the engine is increased when the ethanol content increases [45]. The reason for this is the lower heating value of ethanol.
– Because of the low energy density of ethanol, more ethanol is needed to use than gasoline to get a distance. And this also necessitates larger and heavier fuel tanks [7].
– HC emissions decreases with increasing the amount of ethanol, but it increases excessively in E90 or pure ethanol use [40-42].
– Due to the cetane number of ethanol is low; its self ignition resistance is very high. And that makes difficult to use ethanol in diesel engines [7].
– Because of the high heat of vaporization, ethanol complicates the engine work in cold start [7].
– One of the major disadvantages of the ethanol is the corrosive effect of the water content of the ethanol on the intake system. Due to the corrosive effect of the ethanol, the fuel and the intake system are coated with substances against corrosion [7]. And this increases the cost.

3.5. Methanol

Methanol is the simplest alcohol, and is a light, volatile, colorless, flammable liquid with a distinctive odor very similar to, but slightly sweeter than, that of ethanol. Methanol is obtained by way of distillation under heat of fossil fuels like coal and wood which contain methyl alcohol, applying a set distillation on natural gas, or synthesizing CO and H_2 in a catalytic environment. Common and the most reasonable one of these methods is the method that natural gas is used. Physical and chemical properties of methanol are shown in Table 8 [7].

Like ethanol, methanol is also used in engines mixed with gasoline in certain proportions. However, the use of methanol in vehicles is not as common as that of ethanol. Achieved by use of methanol as a fuel for vehicles, the advantages and disadvantages are as follows [7]:

Table 8 Physical and chemical properties of methanol

Properties	Methanol
Formula	CH_3OH
C/H ratio	0,25
Molecular weight (kg/kmol)	32.04
Lower heating value (kJ/kg)	15910
Research octane number	110
Heat of vaporization (kJ/kg)	1.102
Freezing point (°C)	-97.6
Boiling point (°C)	65.1
Density (kg/m^3)	790

+ Methanol has a high octane number. High octane number allows higher compression ratios and rise of fuel efficiency.
+ Flame temperature of methanol is lower than gasoline, and this provides the combustion improvement and hence the recovery of CO and NO_x in combustion products.
+ Through the use of methanol, CO_2 emissions, which significantly influence the greenhouse effect, decrease.
+ Combustion of methanol is fully realized, creating no combustion particles at all.
+ In case of a leakage, the low evaporation rate of methanol holds the level of concentration in the air low. So, methanol poses less threat than gasoline in case of an accident.
– Cost of methanol is higher than gasoline.
– The use of methanol as an alternative fuel lasts for a short time due to its non-renewable natural resources.
– In our day, energy balance of methanol production is negative. It means that more energy is needed to produce methanol than what methanol gives when it is combusted.
– Methanol has a very low cetane number while it has a high octane number. For this reason, there are some problems of methanol to be used in diesel engines. These problems are the ignition delay of the fuel and the knocking operation of the engine. Methanol can be used in diesel engines in case of using a spark plug system or mixing methanol and diesel fuels at certain proportions.
– Because methanol has a lower energy density (1 L of gasoline equals 1,75 L of ethanol), it requires a larger and heavier fuel tank than that of gasoline for the same range.
– Since methanol has a low evaporation pressure and a high evaporation temperature (methanol uses three times more energy than gasoline to vaporize), it makes the starting of the engine difficult at cold start especially in winter.

3.6. Hydrogen

Hydrogen, which is the lightest element of nature, exhibits a colorless, odorless, tasteless, and a transparent structure. Due to it is very lightweight (1 L of hydrogen is 0.0898 g at 0 °C and atmospheric pressure), it can be found very small amount freely on earth. Table 9 shows physical and chemical properties of hydrogen [46]. Production resources of hydrogen are extremely abundant and diverse. Some of them are water, air, coal and natural gas. Gradually running out of fossil fuels makes water, which has a vast resource of hydrogen production, more advantageous to use. Hydrogen in water (H_2O) is separated by the method of electrolysis [47-49].

Table 9 Physical and chemical properties of hydrogen [7, 46]

Properties	Hydrogen
Molecular weight (kg/kmol)	2.016
Density (kg/m^3)	0.0838
Lower heating value (kJ/kg)	119900
Lower heating value (kJ/m^3)	10050
Boiling point (°C)	-253
Volumetric combustion range (%)	4-75
C/H ratio	0
Heat of vaporization (MJ/kg)	0.447
Octane number	130

Hydrogen can be used in internal combustion engines as fuel. The high auto-ignition temperature (847 to 867 K at 1 atm pressure) and the high octane number of hydrogen show that hydrogen is a more suitable fuel for Otto engines than diesel engines [50]. Some modifications are required in combustion systems of gasoline or diesel engines for the use of hydrogen instead of gasoline or diesel fuels. There are three basic methods used in the designs of hydrogen-fueled engines so far [47, 48];

1. The hydrogen and air mixture is delivered to the inlet manifold of the cylinder at a steady rate. Engine power is adjusted by means of a valve that changes the amount of hydrogen-air mixture.
2. Hydrogen gas is injected into the cylinders under pressure. Because the air comes to the cylinders separately through another inlet manifold, the explosive hydrogen-air mixture does not occur out of the cylinders. This system is more reliable according to the first method. Engine power is adjusted by changing the pressure of hydrogen gas in this system.
3. Analogously to the second method, the hydrogen and air mixture is provided separately to the cylinders in this method. Unlikely, hydrogen is maintained at a normal or medium pressure rather than high pressure, and engine power is adjusted by changing the amount of hydrogen.

On the other hand, there are also some Otto engines with hydrogen supplementation. These engines have small pre-chambers. The pre-chamber attains the place of the spark plug. The main fuel (gasoline, methanol, propane, etc.) is sprayed from the injectors on the intake port to the cylinders. With the hydrogen supplementation, the burning of the hydrocarbon-based fuels is provided at very lean mixture rates. Thus, thermal efficiency is increased, and nitrogen oxide emissions are significantly reduced [51].

Advantages and disadvantages of hydrogen using in automobiles are shown below:

+ The combustion product formed by the combustion of hydrogen and air is water vapor [47]; emissions like CO, CO_2 and HC are not formed due to its carbonless content [20, 52, 53].

+ While the ignition can be achieved in the 0.3 to 1.7 of air excess coefficient values in gasoline-air mixtures, the limit value of the hydrogen-air mixtures reaches to 0.14-4.35 [47].

+ Mass lower heating value of hydrogen is higher than the other engine fuels (hydrogen: 119.93 kJ/g, gasoline: 43.4 kJ/g).

+ In hydrogen fueled engines there are no problems such as steam stopper, condensation on cold surfaces, insufficient evaporation, and poor mixing with air seen in fossil fuel engines [54]. Hydrogen engines present no problems at starting even at -253 °C [55].

+ Thermal efficiency of hydrogen-fueled engines may be increased by 25% providing the increase of compression ratio and establishing a lean mixture [50].

+ The amount of energy required to ignite the hydrogen-air mixture is very low compared to that of other fuels. This feature constitutes an advantage in especially gasoline engines assuring an easy ignition [54].

+ Because hydrogen is a very light gas than air, it reduces the risk of fire rising upward at any accident.

– Two important issues arisen from hydrogen-fueled engines are ignition backwards and preignition events. The low ignition energy of hydrogen causes these two problems [48, 56].

– NO_x emissions formed by high combustion temperatures of hydrogen are higher than that of other fuels [53, 57].

– Production and storage costs of hydrogen are very high [57].

– Volumetric lower heating value of hydrogen is less than other fuels (hydrogen: 8.41 MJ/L, gasoline: 31.8 MJ/L, methanol: 15.9 MJ/L, methane: 20.8 MJ/L).

– Hydrogen is an element, which is difficult to liquefy. It passes to liquid phase at approximately 20 K temperature and 2 bar pressure [58].

– Low density and low viscosity of hydrogen make it possible to seep out through very small cracks or openings of the wall of the environment.

– Hydrogen is a flammable and explosive gas. When it mixes with air at the ratio of 4-75% by volume, it may take fire easily [46].

3.7. Fuel Cell Vehicles (FCV)

Fuel cells, which convert fuel energy into electrical energy with electrochemical principle, are efficient, quiet, environmentally compatible power generation element. In the process of a fuel cell application any combustion process is not concerned; only a chemical reaction takes place. Pure oxygen taken from the air is combined with hydrogen. As a result of this reaction, water and electric are obtained as products. Electric is stored in batteries to be used to provide mechanical movement to the vehicle. [7]. According to the type of the battery and the electrolyte, there are fuel cells available in different varieties. The most commonly used of them is the PEM which is referred to as proton exchange membrane fuel cells. The structure of this fuel cell is as follows [7];

1. Anode: It is negatively charged. There are channels on it emitting hydrogen gas to the catalyst surface evenly.
2. Cathode: It is positively charged. There are channels on it distributing oxygen to the catalyst surface and removing the water produced during the reaction.
3. Catalyst: It causes the chemical reaction between hydrogen and oxygen. The most commonly used types of catalysts are palladium and platinum.

4. PEM: It conveys just positively charged ions of the dissociated hydrogen via catalyst. Protons pass through the fuel cell membrane (or electrolyte in other words) while electrons cannot.

A fuel cell produces 0.7 V electricity on average. 1500-2000 pieces of these fuel cells need to be brought together in series to run an automobile. Power generated by this set of the fuel cells is used to operate electric motors of the vehicle. The hydrogen needed by the fuel cell can be taken from a store of pure hydrogen, or it can be produced from a fuel [7]. Advantages and disadvantages of fuel cell systems are as follows:

+ At the end of the reaction, water is thrown out from the exhaust. Therefore an environmental friendly use is established.
+ It is economical in terms of fuel consumption.
+ It runs quietly and smoothly.
+ The performance of fuel cells does not decrease as time goes, and recharging of the system is not needed.
+ As long as fuel and oxidant are supplied, it continues to produce electricity.
– Fuel cell systems are very expensive according to internal combustion engines. Studies continue to reduce costs reducing the amount of platinum used mainly.
– Utilization life of fuel cells is low for the moment. In order to keep constantly wet the membrane of the PEM fuel cells evaporating water quantity must be equal to the amount of water produced. If water is evaporated too much, the membrane dries, its resistance increases, and finally it cracks leading to gas leakage. Hydrogen and oxygen combine directly through these cracks revealing heat, which damage the cells. If the water is evaporated too slowly, the electrodes are overwhelmed by excess water, the reactants do not reach the catalyst, and the reaction stops. Fuel cell companies and academicians are trying to develop methods for water management.
– There is a difficulty providing hydrogen that is required for the operation of fuel cells.

3.8. Electric Vehicles (EV)

The movement of the vehicle is provided by electric motors in electric vehicles similar to the fuel cell systems. The electricity, which is transferred from an external source, is stored in batteries. Batteries store electrical energy as chemical energy. The most important part that determines the performance of the system is the battery [46]. The advantages and disadvantages of electric cars are as follows:

+ Energy consumption costs of electric vehicles are very low. These costs vary depending on the price of electricity of the country.
+ Due to the absence of lots of moving parts, repair and maintenance costs are low.
+ They run without noise and vibration [59].
+ Well to wheel efficiency of electric vehicles rises up to 40%, while it is about 15% in internal combustion engines [59].
+ EVs have the ability to produce higher torque [59].
+ No emissions emitted to the atmosphere during the operation of the car [60].
+ Electricity can be obtained by renewable methods (biomass, wind, hydro, sun, etc.) [60].

+ Thanks to the electric motors are attached directly to the wheels, there is no need for some parts such as gearbox, differential, and so forth.

– The biggest drawback of EVs is the storage problem of electricity in batteries [46]. That is because the range of EVs is very low.

– Charge duration of battery in EVs is very long compared to that of fossil fuel vehicles.

– Because batteries of EVs are recharged from the mains, the environmental impact of the electricity produced varies from country to country [46, 61].

– The initial purchase cost of EVs is high.

– Charging stations of EVs are not common.

– Silent operation of EVs poses a hazard to pedestrians.

3.9. Hybrid Electric Vehicles (HEV) (Electric Motor + Internal Combustion Engine)

Together with electric motors, an internal combustion engine is used as auxiliary power unit in hybrid systems. There are two types of drive systems regarding the connection type of internal combustion engine and electric motors; parallel hybrid drive system, and serial hybrid drive system [25]. While both the electric motors and internal combustion engine give motion to the wheels in parallel hybrid drive systems, in serial hybrid drive systems only the electric motors give motion to the wheels. In serial hybrid drive systems, the internal combustion engine produces electricity needed by the electric motors like a generator, and sends it to the battery to be stored. The advantages and disadvantages of hybrid systems are as in the following:

+ At low speeds only the electric motors, at high speeds the internal combustion engine, and where performance desired both motors may be used. Therefore, a hybrid system has the advantages of the internal combustion engine and the electric motors, while it gets rid of some of the disadvantages of them.

+ Because exhaust emissions of hybrid systems are low, it is less polluting the environment.

+ Hybrid systems are economical in terms of fuel consumption.

+ The distance of hybrid systems that they take with a tank of fuel is greater than that of a vehicle with an internal combustion engine or electric motors.

– Hybrid systems have both electric motors and an internal combustion engine, so purchase and maintenance costs of it are high.

– Even though they were not directly polluting the air in the use of just the electric motors, air pollution continues due to the internal combustion engines.

3.10. Comparison of Alternative Energy Sources Used in Automobiles

A general comparison of alternative energy sources used in automobiles is given in Table 11. The presented table provides an overall summary of the study. Some of the important options of alternative energy sources are evaluated with respect to the conventional fuels (gasoline and diesel). The rankings are based on the evaluation of the authors on the cited literature in this work. The criteria of the comparison of the alternative energy sources are grouped under three main headings. Initial purchase cost of the vehicle, fuel consumption and maintenance and repair costs are covered in the costs section. In emissions part, the most important emissions of automobiles, which are HC, CO, NO_x, PM and CO_2, are compared. The other part includes features such as range, performance, fueling duration, fuel station availability, fuel renewability, energy efficiency, safety, and noise. Ratings of the alternative energy sources for the criterions are given in four signs; --, -, +, ++ regarding very low, low, high, very high, respectively.

Table 11 Comparison of alternative energy sources used in automobiles

	Gasoline	Diesel	LPG	CNG	Biodiesel	Ethanol	Methanol	Hydrogen	FCV	EV	HEV
Costs											
Vehicle	+ +	+	+ +	+	+	+ +	+ +	+	– –	–	–
Fuel Concumption	–	+	+	+ +	+	–	–	– –	– –	+ +	+
Repair-Maintenance	+	–	+	+	–	+	+	+	– –	– –	– –
Emissions											
HC	– –	–	–	–	–	–	– –	+ +	+ +	+ +	–
CO	– –	+	–	+	+	–	–	+ +	+ +	+ +	–
NO_x	–	– –	–	+	– –	+	+	– –	+ +	+ +	–
PM	+	– –	+	+	–	+	+	+ +	+ +	+ +	+
CO_2	– –	–	– –	+	+	–	–	+ +	+ +	+ +	–
Other											
Range	+	+ +	+	–	+ +	+	–	– –	– –	– –	+ +
Performance	+ +	+ +	+	+	+	+	+	–	– –	– –	+ +
Fueling period	+ +	+ +	+	–	+ +	+ +	+ +	–	–	– –	+ +
Fuel station availability	+ +	+ +	+	–	+	+	–	– –	– –	–	+ +
Fuel renewability	– –	– –	– –	–	+ +	+ +	+ +	+ +	+ +	+ +	–
Energy Efficiency	– –	–	– –	–	–	– –	– –	–	+	+ +	–
Safety	+	+ +	–	+	+ +	+	+	–	+	+ +	+
Noise	–	– –	–	+	– –	–	–	–	+ +	+ +	–

As seen from the figure, in terms of the costs, LPG and CNG are the most advantages energy sources due to their first purchase costs of the vehicle, fuel consumption costs, and repair-maintenance costs compared to that of the others. In this section, FCVs are the worst option with very high costs, however. Regarding the emissions part, FCVs and EVs come to the fore with their environmental friendly electric motors. Hydrogen follows FCVs and EVS in emissions section with its NO_x drawbacks. Gasoline and diesel engines are the most negative choices regarding the other energy sources in terms of the emissions. When we look at the other section, following energy sources are the optimum choices for the subsequent criterion; diesel for range, gasoline and diesel for performance, fueling period, and fuel station availability, and EVs for fuel renewability, efficiency, safety and noise.

4. CONCLUSION

The use of alternative energy sources in automobiles is gaining importance with each passing year due to the rapidly depletion of available energy resources, the rise in fuel prices depending on this depletion, and environmental factors. The most important factors in the acceptance of alternative energy sources are the initial purchase cost of the system, the cheapness of the fuel, station availability and filling duration of the fuel, vehicle range and performance, and the environmental impact. While it is difficult to meet all of these factors, the energy source that takes the highest rate will be preferred by consumers. In this study, some important information is given about the features of alternative energy sources used in automobiles, and this energy source has been compared with each other for some distinguishing factors. According to the comparison, LPG and CNG seem to be best alternative fuels for economical reasons, while electric and fuel cell vehicles stand out as their emission advantages.

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