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Environmental, Economic and Technical Status of Fuel Cell Technology

Arif Emre AKTAŞ[1] Abdulkadir YAŞAR[2]*
[1]Department of Automotive Engineering, Faculty of Engineering and Architecture, Çukurova University, Adana, Turkey
[2]Department of Mechanical Engineering, Ceyhan Engineering Faculty, Çukurova University, Adana, Turkey

*Corresponding Author:
E-mail:ayasar@cu.edu.tr

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Abstract

With the increasing technology and population environmental damage of fossil fuel based energy production technologies has been reaching critical level. For this reason, studies are implementing for environmentally less harmful alternative energy sources. Fuel cells as a possible major energy carrier for the future, offers higher efficiencies and significantly lower emissions than conventional technologies. Their efficiency isn't limited to Carnot cycle. They also operate quietly and have a modular construction that is easily scalable. These features makes fuel cells attractive for a large range of potential application areas. This paper presents a comparative overview of fuel cell technology.

Keywords: Fuel Cells, Environmental effects, Sustainability, Reliability, Cost

INTRODUCTION

A fuel cell is an electrochemical device which converts chemical energy of fuel directly into direct current (DC) electricity. It is very similar to batteries: two electrodes divided by electrolyte. Battery can't supply continuous energy. Besides fuel cells can be fed.

Typical process of electricity generation from fuels involves several energy conversion steps: Combustion of fuel converts chemical energy of fuel into heat. This heat is used to boil water and generate steam. Steam is used to run a turbine which converts thermal energy into mechanical energy. Finally, the mechanical energy is used to run a generator that generates electricity [1].

A fuel cell circumvents all these processes and generates electricity in a single step without involving any moving parts [2]. This simplicity attracts attention. The one step nature of this process in comparison to conventional has several unique advantages. For example, current fossil fuel based energy generation methods are very harmful to the environment. Besides fuel cells produce less greenhouse gases. If fuel is pure hydrogen, products of fuel cells are only water and heat [3].

In fuel cells there is no mechanical efficiency lost. Because there is no moving part during working in the fuel cell stack therefore, fuel cell stack is silent and vibration-free. Fuel cells also provide high efficiencies at partial loadings and at small sizes - both are important advantages over traditional energy converters [4]. Shortly, fuel cells provide a cleaner, more efficient, and possibly the most flexible chemical-to-electrical energy conversion [5].

Since the beginning of the industrial revolution levels of greenhouse gas emissions are increasing. In 2015, carbon dioxide concentrations began to reach above 400 ppm. In other words, during last 50 years it increased more than 25% [6,7]. This situation affecting the earth's climate adversely. As stated above, if fuel is pure hydrogen there is no carbon dioxide emission during the fuel cell stack operation. Nevertheless, this environmental friendly nature of fuel cell depends upon the production route of its fuel [8]. Hydrogen can't naturally exist on the earth. If hydrogen production is made from fossil sources such as methane and coal greenhouse gases emitted to atmosphere. Besides if it is produced from renewable sources such as solar and wind energy environmental impact will be lowest level [9,10]. Therefore well to wheel emission values gives more objective comparison results. Figure 1 shows CO_2 emissions per kilometer "from well to wheel" for different applications as a future estimation. According to the figure most fuel cell types have better result.

EFFICIENCY

The amount of heat that could be converted to useful work in a heat engine is limited by the ideal reversible Carnot efficiency which proposed by Nicolas Carnot.

The Carnot engine efficiency is defined as:

$$\eta = \frac{T_H - T_L}{T_H} \quad (1)$$

Where T_H and T_L are the absolute temperature at the engine inlet and the absolute temperature at the engine exit, respectively. Carnot efficiency cannot be applied to fuel cells because a fuel cell is not a heat engine; instead, it is an electrochemical energy converter [2]. On the other hand, Change in the Gibbs free energy of the electrochemical reaction gives the maximum obtainable electrical work in a fuel cell operating at constant temperature and pressure [12].

The ideal efficiency of a fuel cell:

$$\eta_c = \frac{\Delta G}{\Delta H} \quad (2)$$

Where ΔGf is the change in Gibbs free energy of formation during the reactions and ΔHf is the change in the enthalpy of formation. There are two types of ΔHf value; these are HHV (higher heating value) and LHV (lower heating value) if the product water is in liquid form and gaseous form, respectively.

The most commonly used way of expressing efficiency of a fuel cell is based on the change in the standard free energy for the cell reaction:

$$H_2 + 1/2O_2 \xrightarrow{yields} H_2O \quad (3)$$

$$\Delta G^o = G^o{}_{H_2O} - G^o{}_{H_2} - 1/2G^o{}_{O_2} \quad (4)$$

At room temperature, system chemical energy ΔH is 285,8 kJ/mole and free energy for useful work, ΔG is 237,1 kJ/mole, so the thermal efficiency of an ideal fuel cell operation with pure hydrogen and oxygen would be [13,12]:

$$\eta_c = \frac{237,1}{285,8} = 0,83 \quad (5)$$

In a fuel cell conversion fuel to energy occurs in one step without the need for multiple steps, they are able to achieve much higher conversion efficiencies. Due to one step nature of energy conversion reaction, they have higher conversion efficiencies. For example, PEM & SOFC have electrical efficiencies over 60% [14] and MCFC can achieve combined electrical and thermal efficiencies of over 90% [15,16] when used for CHP applications. Fuel Cell vehicles can be up to 2-3 times more efficient than current gasoline vehicles [16,17]. Figure 2 illustrates the efficiency of fuel cells and other energy conversion devices with respect to system power output.

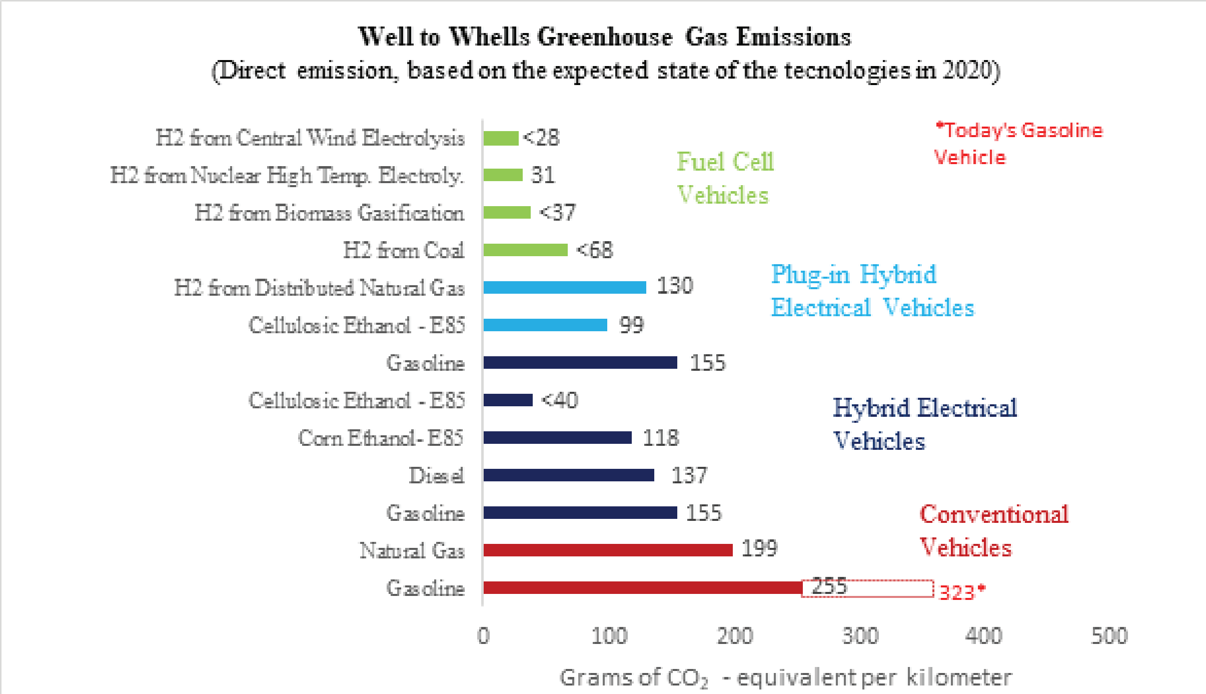

Figure 1. Well to wheels analysis of potential reduction in greenhouse gas emissions for different sources [11]

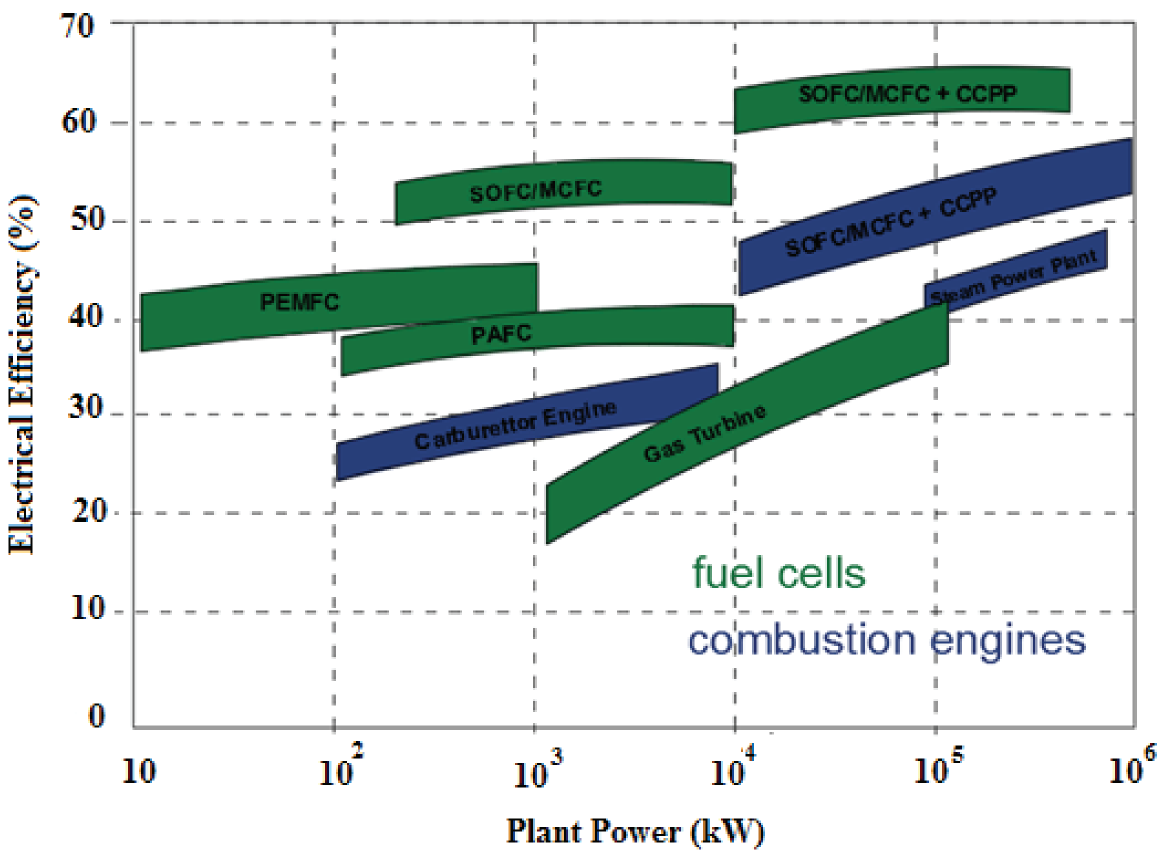

Figure 2. Comparison of Energy Efficiencies [18]

MODULARITY and FLEXIBILTY

Fuel cells are intrinsically modular. Being independent of size and load fuel cell keeps its efficiency almost stable. Energy output of fuel cell power plant can range between single kilowatt sizes to multi megawatt power system [19]. Moreover, its application field can comprise transportation, stationary and portable application [20].

Single fuel cell produce relatively small amounts of electricity, but when stacked or placed in series like batteries, the voltage increases. The fuel cell size can be adapted by simply changing the number of elementary cells and the available area [21].

Fuel cells are the ideal solution when space is limited. Fuel cell installations are relatively small compared to wind and solar energy. Four Fuel Cell Energy power plants which produces 11.2 MW occupy nearly an acre of land [22]. In comparison, wind power requires an average of 17 acres of land to produce one megawatt of electricity [23]. For the safe of birds wind turbines requires large areas.

SUSTAINIBILTY

Hydrogen is the most abundant element in the universe. It can be produced from a variety of sources such as natural gas, electrolysis, coal, sun. It is essential that in the case of producing hydrogen from conventional methods utilizing fossil fuels will not make hydrogen completely clean in terms of pollutant solid wastes and other environmental deterioration [24]. Nevertheless, fuel cell systems can help to obtain sustainability when they operate on hydrogen harnessed from sustainable energy resources. Such hydrogen fuel cell technologies compose alternatives to conventional fossil-fuel energy technologies and are more efficient, environmentally friendly and sustainable [25]. A study for fuel cell vehicle indicated that hydrogen obtained from solar energy showed highest energy conversion and lowest emission performance nonetheless, hydrogen from natural gas showed best economical performance [26].

RELIABILITY

Reliability is the ability of a system to perform its function adequately (i.e. without failure and within designated performance limits) for a specified period of time, in its life cycle conditions [27].

Reliability is expressed mathematically as [28]:

$$R(t) = \int_{t}^{\infty} f(x)dx \qquad (6)$$

Where f(x) is probability of failure density function and t is the time period. Practically, fuel cell systems have no rotating or moving parts, therefore it has lower probability of failure than combustion engines and turbines [29-31]. A UK-based fuel cell developer has reported that endurance testing of a fuel cell has achieved a runtime of 10,000 hours on a third party automotive industry durability test without any significant signs of degradation. This is equivalent to 482803 driven kilometers and exceeds the current 2017 US Department of Energy target of 5,000 hours [32]. Fuel cells serve as both standby and primary power sources. In case of electric grid failure, they can start quickly in a reliable manner as a backup power source. Fuel cells can also meet daily energy needs and provide consistent, high-quality power regardless of electric grid breakdown [33].

SILENT / VIBRATION-FREE

With no moving and rotating parts, and due to its chemical nature fuel cell stacks are silent and vibration free. Only possible noise sources are blowers and fans [34]. Therefore this important feature makes the usage of it on broad application area. As seen from the Figure 3, fuel cell system noise is almost the half level of diesel engine, gas turbine and petrol engine. In a fuel cell system needs pumps, compressors and other moving parts are required which produce vibration and sound, but these are on a different level of magnitude than the noise and vibration produced by traditional combustion engine technologies [36].

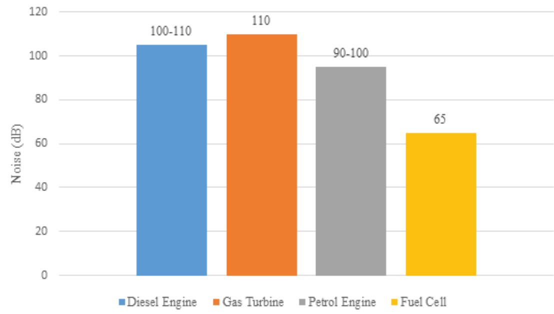

Figure 3. Comparison of Noise Emissions between the four main engine types [35].

COST

Fuel cell technology is its early age compared to other energy technologies. Due to the lack of fully automated manufacturing technology, capital cost estimation is difficult. Nevertheless, cost prediction can be implement if there is a comprehensive inventory of the cell stack [37].

Some of the components used in fuel cell are very expensive. Main reasons of the high cost are: the dependence on platinum for catalysts, methods of delicate membrane fabrication, and the coating and plate material of bipolar plates [38]. Particularly, the catalyst literally costs as high as gold. A catalyst is a substance that enhances a chemical reaction rate without itself being consumed [39]. Intrinsically, it must remain chemically inert under the conditions required for the reaction. Almost all catalysts for hydrogen fuel cells contain platinum, which costs over $35 per gram [40]. Another issue about platinum is being oxidation, migration of nanoparticles, loss of active surface area, and corrosion of carbon support [41]. Much of the current research on fuel cells to reduce cost, focuses on minimizing the amount of platinum needed for catalysis. According to DoE, quantity of platinum in PEM-FC has decreased approximately 80% during the last ten years [42]. Also researches are implementing to replace platinum by non-noble metal catalysts [43]. According to the figure 4, cost per kW of PEM fuel cell decreased from $124 to $53 in the time interval between 2006 and 2015. In order to compete with internal combustion vehicle industry, estimated fuel cell system cost per kilowatt should be $30/kW [44].

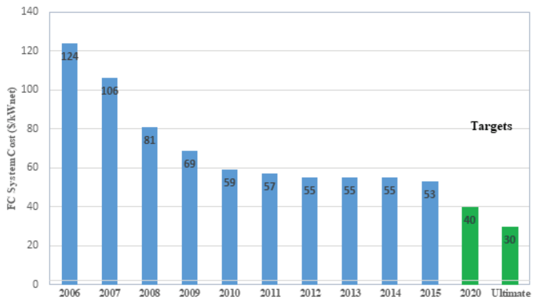

Figure 4. Modeled cost of an 80-kWnet PEM fuel cell system based on projection to high-volume manufacturing (500,000 units/year) [45].

INFRASTRUCTURE of HYDROGEN

Hydrogen is the most plentiful element in the universe, however element state of it is not found in nature since earth gravity is not strong enough to keep it at gas state in the atmospheric condition. For this reason, it has to be manufactured [46]. The reforming of natural gas or other hydrocarbon products is responsible for over 90 percent of total hydrogen production of the world [47]. The primary reason of preferring those methods are having low production cost [48]. Figure 5 shows average production cost comparison and environmental comparison of selected production methods. In can be inferred from the figure that fossil fuel based production methods are the most environmentally destructive. Being renewable sources, solar and wind electrolysis methods have remarkably higher costs. In the near future, biomass gasification method which can utilize wide range of sources, regarded to turn most probable substitute to petroleum [49,50].

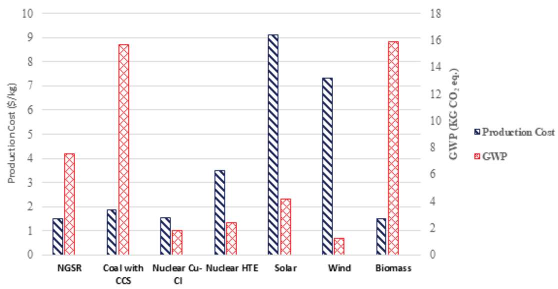

Figure 5. Global warming potential and average production cost of selected hydrogen production methods [48].

Hydrogen, smallest molecule of the universe, has high energy density by weight but low energy density by volume. Hydrogen is also a highly reactive molecule. These inherent properties make the storage of hydrogen a big issue especially for mobile applications [51].

Hydrogen storage methods can be divided basically into three groups: (1) Storing at gas state under pressure. (2) Storing at liquid state at very low (cryogenic) temperature. (3) Storing as a compound storing or linked to a medium [51]. Table 1 summarizes the mostly used hydrogen production methods. Today, research and development study is carried out to find to store hydrogen at minimum weight and volume in a safer and cheaper manner.

Table 1. Overview of mostly used hydrogen storage methods [51, 52-55]**.**

Methods	Details	Advantages	Drawbacks
Gaseous Hydrogen	• Pressure is up to 800 bar • Most frequen storage method	• Low energy consumption	• Risky due to high pressure • High vessel weight required
Liquid Hydrogen	• Atmospheric pressure, 20,4 K in insulated vessel.	• Higher energy density than pressurised hydrogen	• At least 35% of fuel energy consumed to liquify. • Evaporates easily during trans-portation and refuelling
Underground storage	• Storing hydrogen in depleted underground fields	• Cheap • Suitable for large storage • Good for long term storage	• Limited to certain locations
Metal Hydride	• Hydrogen combines either physically or chemically - Magnesium hydride (MgH_2), calcium hydride (CaH_2), sodium hydride (NaH)	• Safe • No hydrogen loss • No additional power supply is required	• Low gravimetric energy denstiy

CONCLUSIONS

In this paper, a brief comparative study is carried out to present environmental, economic and technical status of fuel cell technology. Following conclusions can be drawn out from this study.

Fuel cell technology is environmentally friendly. Well to wheel analysis indicated that fuel cell vehicle greenhouse gas emission is lower than all vehicles powered by internal combustion engines. Also it has better performance than most of electric and hybrid vehicles.

Fuel cells have higher theoretical efficiency than heat engines. Because fuel cell efficiency isn't limited by ideal reversible Carnot efficiency.

Fuel cell has flexible application area which can range between mobile phones to large power plants.

Sustainability can be obtained in fuel cell technology if hydrogen source is sustainable.

Due to having no moving and rotating parts (except for fan, pump and blowers as an external unit) and its chemical nature, fuel cells are reliable and silent.

The biggest obstacle in front of fuel cell technology is high cost. Main reason is dependence on dependence on platinum. To compete with internal combustion technology, alternative catalyst should be developed. Hopefully, cost of fuel cell power fall more than 50 % in the last decade.

Due to its natural properties, storage of hydrogen is still a big issue especially for mobile applications.

Environmentally friendly hydrogen production method needs to be cheaper in order to leave behind fossil fuel based production methods.

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