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Types and applications of hydrogen fuel cells in transport

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The article summarizes the types of hydrogen sources and the possibilities of using hydrogen in fuel cell technologies. The types of hydrogen fuel cells and solutions used in hydrogen powered drives were discussed. The current economic and ecological aspects affecting the possibilities and profitability of using various types of hydrogen as an alternative fuel in various forms of transport were analyzed, and forecasts for the development of this form of propulsion and power supply in transport for the coming years were presented. It was concluded that only a simultaneous increase in hydrogen production, through an increase in demand or technological development, combined with a decrease in the cost of hydrogen cells down to a level of at least $40/kW, would enable the proliferation of hydrogen technologies in all modes of transport.

1. Introduction

New trends in industry and transport are accelerating the development of new power and propulsion technologies, especially those with lower exhaust emissions than the currently available conventional solutions. The use of hydrogen as fuel dates back to 1806, when de Rivaz built an internal combustion engine powered by hydrogen and oxygen [5]. In recent decades, the use of hydrogen as an additive to conventional fuel in gasoline and diesel engines was also considered, but none of these solutions showed a sufficient increase in the efficiency of the combustion process to justify the high costs of an additional electrolysis system (HHO device) for hydrogen production [10].

It should be noted that the cost of hydrogen fuel, both in terms of price and the environmental impact, is independent of the hydrogen cell technology used. Which has a significant impact on the potential applications and competitiveness of hydrogen propulsion [7]. Hydrogen production costs vary depending on the production method and the energy source used for its production. The literature distinguishes this by classifying hydrogen by colors. Hydrogen is classified into white, gray, black, brown, blue, turquoise, purple, pink, red, and green, depending on the method of its production [4]. Some of the methods discussed are still only partially developed or require further research to enable efficient fuel production. The meaning of each of the colors of hydrogen and its production method was explained in Table 1. The contribution of each of the different hydrogen production methods in total production varies from country to country, and can depend on a number of factors. Despite the significant advantages of green hydrogen in terms of its environmental impact, the level of its production completely depends on the degree of dissemination of alternative energy sources. Hence, it is possible to promote the growth of green hydrogen production indirectly through investments and subsidies for wind and solar power plants.

2. Hydrogen fuel cell technologies

2.1. Phosphoric Acid Fuel Cell

Cells based on acids (e.g. phosphoric acid) in liquid or solid form, called PAFC (Phosphoric Acid Fuel

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Cell) or SAFC (Solid Acid Fuel Cell). PAFC operate at temperatures in the range of 150–200°C, which leads to large heat losses in the system, limiting the efficiency of systems using fuel cells of this type. However, they also show a much greater tolerance to the presence of CO in the system, up to 1.5% [11], which allows them to operate in a wider range of conditions and with fuels that cannot be used in other cells, such as with a proton membrane cell. The most frequently used electrolyte is the phosphoric acid (H_3PO_4), which is trapped in a silicon carbide mesh. SAFC are characterized by the use of a solid acid as the electrolyte. In this type of a cell, the acid is in a highly ordered form, while at the operating temperature of 140–150°C (for cells using cesium bisulfate, or 200–300°C for other types of cells), there is a phase transition to a super-proton structure, significantly increasing the electrolyte conductivity. In this form, the cesium electrolyte increases its conductivity several times, allowing the cell to achieve a 50% efficiency. Unfortunately, for SAFC cells, high temperature leads to large heat losses, while the chemical products of sulphates lead to wear and deterioration of the cell's anode.

Table 1. Hydrogen colors explanation

Hydrogen color	Production method
White	Extracted from natural geological sources in the form of H_2
Grey	Methane reforming
Black	Black coal gasification
Brown	Brown coal gasification
Blue	Methane reforming and capturing the accompanying carbon dioxide emissions
Turquoise	Methane pyrolysis
Purple	Chemo-thermal electrolysis of water powered by energy and heat from a nuclear power plant
Pink	Nuclear-powered water electrolysis
Red	High-temperature catalytic water separation fed with heat from a nuclear power plant
Green	Water electrolysis powered by energy from renewable sources

2.2. Alkaline Fuel Cell

Alkaline cells are an older but well developed technology. These types of cells were used in space shuttles for example. A characteristic feature of alkaline cells is the use of a porous barrier soaked in an alkaline liquid, often potassium hydroxide (KOH). The main problem of using potassium hydroxide electrolyte cells is its tendency to absorb carbon dioxide, thus reducing the electrolyte to potassium carbonate (K_2CO_3), which does not have the chemical properties that would allow the cell to work. As a result, alkaline cells are usually fed with pure hydrogen and pure oxygen to avoid carbon dioxide contamination of the cell. The chemical reactions at the cathode begin with:

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \quad (1)$$

Then OH^- ions migrate through the electrolyte to the anode, where it reacts with hydrogen:

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \quad (2)$$

The first practical application of this cell technology took place in the historical Apollo missions. Depending on the selected electrolyte, the operating temperature of this type of cell changes, for potassium hydroxide it is 250°C, while for electrolyte with 30% potassium hydroxide (KOH) it operates at just 120°C. Alkaline fuel cells can work in the low temperature range as well (room temperature up to 90°C) and in such conditions they are more efficient than acid or proton exchange membrane based cells.

2.3. Solid Oxide Fuel Cell

Solid oxide cells known as SOFCs (Solid Oxide Fuel Cell) use a solid electrolyte that allows the flow of O^{2-} oxide anions. In this type of cells, the most commonly used electrolyte is zirconium oxide (ZrO_2) doped with yttrium oxide (Y_2O_3). This solution has a very similar principle of operation to other types of fuel cells, the main difference is which compound flows through the electrolyte. In the case of most fuel cell types, the hydrogen atoms are passed through the electrolyte and then bind to oxygen on the other side of the system, while for SOFCs, oxygen is the one that flows through the electrolyte into the hydrogen chamber [3]. The main result of this type of design choice is the lack of recirculation of unoxidized hydrogen. The operating temperature of SOFC cells is over 800°C, which makes it difficult to use this type of cell in some solutions. The use of oxygen permeable electrolyte instead of fuel (typically hydrogen) allows SOFCs to be fed with various types of fuels. Apart from hydrogen (H_2), such cells can also be fueled with carbon monoxide (CO), hydrocarbon fuels (CH_4 group forms) or biogas. The lack of liquid electrolyte also reduces the risk of electrolyte leakage, and due to the high temperature, the fuel can be reformed in the cell. The chemical process that takes place at the cathode is:

$$O_2 + 4e^- \rightarrow 2O^{2-} \quad (3)$$

While the anode produces the reaction:

$$2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^- \quad (4)$$

Molten Carbonate Fuel Cells (MCFC) use carbon dioxide to enable the hydrogen oxidation reaction. Their operation is based on using an electrolyte, typically a molten carbonate salt with addition of lithium carbonate (Li_2CO_3) and potassium carbonate (K_2CO_3), which passes oxygen (O_2) particles after combination with carbon dioxide (CO_2) to carbonate anions (CO_3^{2-}). This occurs through reactions at the cathode:

$$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \quad (5)$$

where carbon dioxide is recirculated from the anode reaction while the carbonate anions pass through the electrolyte:

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \quad (6)$$

2.4. Proton Exchange Membrane Fuel Cell

Proton Exchange Membrane Fuel Cells (PEMFC or PEM) are the most popular solution used in transport. The main characteristic of PEMFCs is a polymer membrane that separates the electrodes, acting as an electrolyte and allowing the flow of protons (hydrogen nuclei). Hydrogen on the anode side dissociates into protons and electrons (7). The protons released in this way flow through the membrane to the cathode, where they combine with the oxygen on it along with the electrons (8), after they have travelled through the electric circuit (Fig. 1). The chemical reactions occurring at the cathode are the ionization of hydrogen molecules:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (7)$$

While at the complementary reaction at the anode is their oxidation into water:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (8)$$

Such fuel cells use plates made of metal, graphite, carbon composites or carbon-polymer composites. In the main part of the cell there are also catalytic layers added at the membrane boundaries to catalyze the processes taking place in the cell. Due to the noble metals used as catalysts, PEMFCs can become contaminated with hydrogen oxide, which makes it important to ensure a high level of purity of the hydrogen fuel.

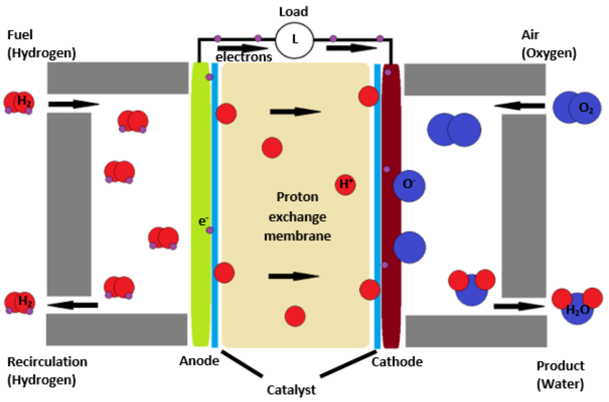

Fig. 1. PEMFC construction schematic and operation principle

3. Transport applications

Due to their high power density and very good dynamic properties, PEMFCs have found a wide range of applications in transport. Most notably these types of fuel cells were used in road, but also rail vehicles. Among the new rail solutions using fuel cells all where the fuel cell technology was officially announced used PEMFC technology. This includes modifications of rail vehicles, such as the already existing Canadian Green Goat electric shunting locomotive, who got a new hydrogen powered version called HH20B. The French Alstom has similarly presented a hydrogen version of their diesel powered passenger railcar Coradia LINT, with the new PEMFC variant called Coradia iLint. New hydrogen propulsion solutions began being developed in Poland as well. PESA has recently presented their new concept of a hydrogen variant of the SM42 type shunting locomotive, which they called SM42 6Dn (Fig. 2) [1].

Fig. 2. The SM42 6Dn hydrogen shunting locomotive presented by PESA at the TRAKO rail fair

Despite their numerous advantages, however, there are also a number of problems associated with the use of PEMFCs in vehicle propulsion systems. The main disadvantages of these types of cells are their cost, service life, susceptibility to carbon monoxide contamination, and the need to maintain appropriate temperature and humidity in the cell.

Controlling the water level in the cell is very important and requires maintaining an appropriate balance between the rate of water evaporation and the production of water during cell operation. If the water evaporates too quickly, the membrane dries up, which may cause it to break and damage the cell, while if the water evaporates too slowly, it begins to accumulate on the electrodes, inhibiting the cell's functions. It is also necessary to keep the cells at the same temperature, as temperature differences can cause thermal stress in the system.

The lifetime of modern PEMFCs is considered sufficient, they are able to reach even 5,000 hours of operation [8] which enables their use in vehicles, and their relatively low weight significantly facilitates their use in various forms of transport.

The primary problem for this cell type is their high cost. Similarly to new energy storage technologies, such as semiconductor batteries, the main problem in reducing the production costs of fuel cells is related to the economies of scale. High production costs lead to high retail prices, which reduce the interest as well as the range and scope of viable applications, resulting in lower demand for this product, which ultimately results in the lack of demand for more efficient, faster and cheaper mass production. According to a projection made by the US Department of Energy, production of 100,000 vehicles could reduce the cost of fuel cell systems to $67/kW, while the production of 500,000 vehicles per year could reduce these costs down to as little as $55/kW (Fig. 3). The adopted goal, which is estimated to allow the widespread dissemination of fuel cell technologies, is reaching the cost of $40/kW.

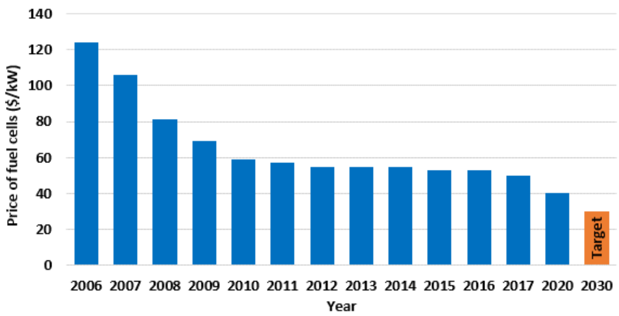

Fig. 3. Change in the cost of fuel cells in the last 15 years (according to Office of Energy Efficient and Renewable Energy)

4. Technological and market limitations

In addition to the operating costs of hydrogen fuel cells, hydrogen itself should also be taken into account, the production cost of which depends directly on the energy price, and the environmental impact it generates depends on the energy source. Since the ultimate goal of using hydrogen as a fuel is to reduce greenhouse gas emissions, most studies assume that hydrogen would only be produced using renewable energy. Especially from sources that have high variations in the level of energy produced throughout the day, such as solar panels and wind turbines. In such systems, situations often arise where excess energy is produced that cannot be used. Hence, using this energy to produce hydrogen, which can then be used to power the cells at a later time, is an energy storage method based on renewable energy sources. The use of renewable energy electrolysis, however, is limited due to the competition in the form of relatively cheap hydrogen produced from natural gas extraction. However, despite the rapid development and popularity of hydrogen as a fuel, the current demand does not reflect the broad plans for the use of hydrogen presented by various countries, companies and institutions. So far, the demand for hydrogen has been almost entirely caused by refineries for the refining of fuels and by chemical plants for the industrial production of ammonia (Fig. 4). Wide possibilities of hydrogen applications, especially in transport, would require a significant increase in hydrogen production while maintaining or even reducing its price [6]. In addition, as the transition to hydrogen fuel as a power source for vehicles is driven primarily by greenhouse has emission reduction efforts, most new hydrogen production is expected to be powered by clean renewable energy. This is popularly referred to as "green hydrogen" production.

The use of hydrogen as a solution for the long-term storage of energy produced from renewable sources enables the reduction of energy losses caused by overproduction during low electricity demand periods by these sources. However, this presents another problem which has mainly to do with the storage of hydrogen itself. The capacity of hydrogen tanks is limited by the physicochemical properties of this fuel, requiring low temperatures and high pressures due to the low energy density of the hydrogen fuel. There are numerous technologies that allow the use of hydrogen compression methods for fuel storage, both in stationary and transport solutions [12]. The possibility of wider use of hydrogen fuel in terms of refueling stations has existed for some time, and in 2013 there were 224 hydrogen refueling stations registered worldwide [2]. The use of hydrogen as fuel is therefore not limited by the current state of fuel tank technology or storage and refueling methods, but rather to greater extent by the lack of sufficient market demand and production.

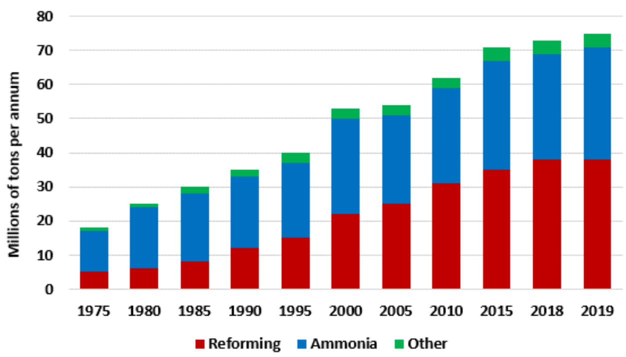

Fig. 4. Hydrogen demand sources in the years 1975-2019

To adapt the hydrogen fuel production industry to solutions focused on production using a hydrolysis process would require an increased input of electricity compared to the energy cost associated with the production of white, black, gray or turquoise hydrogen. In order for the hydrogen production by hydrolysis to not have a greater negative impact on the environment than simply its extraction, reforming or gasification, the additional demand for electricity would need to be covered by an increased production of energy from renewable sources. This mainly applies to countries such as Germany or the Netherlands, for which the increase in energy demand would be the highest in Europe (Fig. 5).

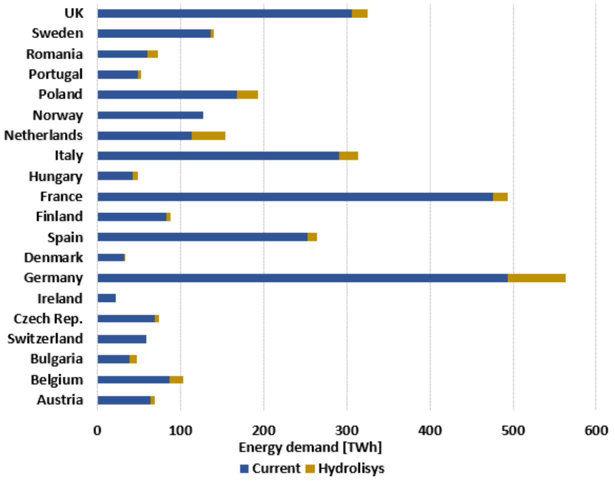

Fig. 5. The current energy demand of European countries and the demand increase when using electrolysis hydrogen production [9]

This further indicates a need to expand and improve the renewable energy production technologies, and investment into new power plants running on renewable energy sources. Some of these might need to be located in different regions to maximize their efficiency, such as solar power plants already built in Morocco, or wind turbines in Northern Scotland. At that point another issue arises in the form of ensuring local stability, and a safe and efficient transfer of the generated electricity to the EU energy grid, which itself needs to be expanded to meet the upcoming needs of charging for the growing fleet of electric vehicles.

5. Conclusions

Assuming a further increase in the share of energy production from renewable sources and an increase in green hydrogen production along with the associated decrease in costs, it can be expected that obtaining cheap hydrogen fuel will become easier in the coming years. Moreover, further development of the hydrogen cell technology may make this technology more competitive on the market and help enable the spread of its applications. Further investments in the development of renewable energy sources, as part of activities carried out by EU Member States, lead to a growing share of these energy sources in total energy production. Due to the operating characteristics of wind farms and solar panels, the electricity they produce is not predictable nor can be adjusted to the energy demand on an ongoing basis, as is done in the case of gas-fired power plants, which are used to supply electricity for the dynamic variations in energy needs. Hydrogen production can be used as a method of energy storage, as an alternative to the most commonly used pumped storage hydropower plants. Combined with reducing the hydrogen fuel cells cost to the expected optimal level of $40/kW, the use of hydrogen fuel and hydrogen cells can enable a smooth transition from fossil fuels to carbon-free renewables. Further development of hydrogen cell technology in Europe and around the world is necessary to meet the CO_2 directives.

Nomenclature

PAFC	Phosphoric Acid Fuel Cell
SAFC	Solid Acid Fuel Cell
SOFC	Solid Oxide Fuel Cell
MCFC	Molten Carbonate Fuel Cells
PEMFC	Proton Exchange Membrane Fuel Cells

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