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HYDROGEN AS A VEHICLE FUEL

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RESEARCH ARTICLE

ABSTRACT: Limited oil reserves and the ecological consequences of its use in motor vehicles impose an increasing need for alternative energy and drives. The use of hydrogen as the fuel of the future is one of the solutions whose commercialization has begun in the past few years. Although its use has no impact on the environment, the production process, which is still expensive, does. Transport and storage of hydrogen, as well as advanced, but expensive technologies for its use, also present additional challenges, which are examined by the authors of this review paper through few topics. The properties of hydrogen, the way it is obtained, stored and transported are presented. Particular attention is paid to the method of obtaining the propulsion energy by combustion or by using different types of fuel cells. The paper also covers some examples of vehicles powered by hydrogen.

KEY WORDS: hydrogen fuel, fuel cells, ecology, logistics problems

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VODONIK KAO POGONSKO GORIVO VOZILA

REZIME: Ograničene rezerve nafte i ekološke posledice njene upotrebe u motornim vozilima nameću sve veću potrebu za alternativnim izvorima energije i pogonima. Primena vodonika kao goriva budućnosti je jedno od rešenja čija je komercijalizacija počela u poslednjih nekoliko godina. Iako, njegova upotreba nema uticaja na životnu sredinu, proizvodni proces, koji je i dalje skup, ima. Transport i skladištenje vodonika, kao napredne, ali skupe tehnologije za njegovu upotrebu, takođe predstavljaju dodatne izazove, koje autori ovog rada analiziraju sa više aspekata. Prikazane su: karakteristike vodonika, načina dobijanja, skladištenja i transporta. Posebna pažnja je posvećena načinu dobijanja pogonske energije sagorevanjem ili primenom različitih vrsta gorivih ćelija. U ovom radu su prikazani primeri vozila pogonjenih vodonikom.

KLJUČNE REČI: vodonik kao gorivo, gorive ćelije, ekologija, problemi logistike

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1. INTRODUCTION

Oil, coal and natural gas are three major energy sources of the present. The share of sources such as nuclear energy, geothermal springs and wind is significantly smaller, whereas so-called alternative fuels and innovative technologies take only a small part. Unfortunately, oil is not a renewable source of energy. According to the forecast [8], drastic changes will happen in year 2040 (Figure 1). By that time, the production of crude oil will increase, but it will be followed by a sudden decrease; thus, it is expected that in 2100 major sources of energy will be coal, renewable liquid and gaseous biofuels, solar energy, wind energy, as well as hydropower and nuclear energy. Also, there is the problem of unequal distribution of oil as a natural resource - for many countries, it is an import energy source whose price varies.

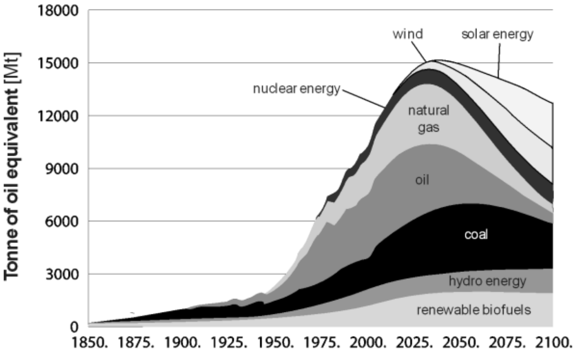

Figure 1. Forecast of energy demand

Estimates from 2014 point to the fact that 98% of motor vehicles on the planet use IC engines running on hydrocarbon-based fuels. According to the statistical data [32], the number of motor vehicles in the world in 2014 was over 1.23 billion (Figure 2). The number of vehicles in 1970 was approximately five times smaller and in only 16 years (by 1986) the number of vehicles has doubled. In 2009, the number of motor vehicles on the planet already exceeded 1 billion. In only five years (from 2009 to 2014), the number of vehicles increased by more than 200 million – more than 20%. It is estimated that, by the year of 2035, the number of vehicles on the planet will reach two billion [31]. Such a forecast is not encouraging at all, because of the fact that limited sources of energy are being used, primarily oil, which still represents the world leading energy source for the motor vehicles, and also because of the global pollution of our planet due to exhaust emission of IC engines.

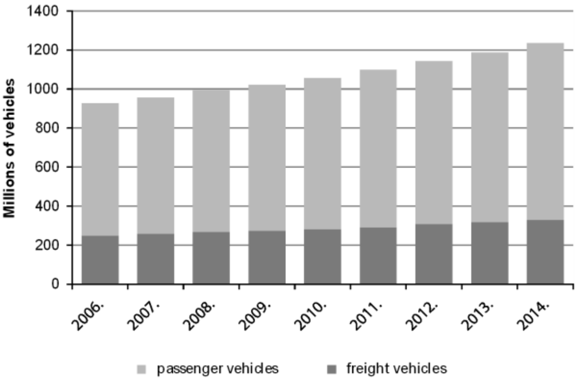

Figure 2. Total number of vehicles in the world

It should be emphasized that the research has shown that the increase in fuel consumption while driving is followed by the increase in harmful exhaust emission, but in different proportions for various emission components. For example, if the difference in fuel consumption caused by different driving techniques is 21%, the difference in emission can be 72% for hydrocarbons and 48% for nitrogen oxides [22]. The content of carbon dioxide in exhausts is proportionate to the fuel consumption. According to the data provided by the U.S. Environmental Protection Agency, transportation represented 27% of total U.S. GHG emissions in 2015, 83% of which is caused by on-road vehicles [10]. Each liter of petrol combusted in the vehicle engine produces 2.35 kg of CO2 on average, whereas each combusted liter of diesel releases in to the atmosphere 2.69 kg of CO2 on average [6]. Average passenger vehicle emits 4.7 tons of carbon dioxide over one year [11]. This clearly shows that fuel-efficient driving not only saves fuel, but also contributes to the environment protection. Carbon dioxide is present in the air as a natural ingredient and it is not considered a pollutant in terms of exhaust emission of motor vehicles. However, it is considered as one of the major causes of climate changes due to “greenhouse effect”. Atmospheric CO2 levels rose to 395 ppm in 2012, making the second highest jump since 1959, when the measurements of atmospheric carbon dioxide levels began [5]. The direct relationship between exhaust emission and human health points to the significance of the reduction of the emission produced by fuel combustion.

Limited sources of oil and increased exhaust emission of motor vehicles represent the global challenge for the researchers. The problems are solved by applying new solutions on existing IC engines, as well as by using alternative fuels such as liquefied petroleum gas, compressed natural gas or certain kinds of biofuels. However, a special way to solve the above-mentioned problems is to develop and use modern solutions, such as hybrid vehicles, electric vehicles and vehicles running on hydrogen.

2. HYDROGEN

If we want to decarbonise our energy footprint, renewable energy source are the way forward. They can either be consumed directly, like biogas, or can be transformed into electricity like hydro, solar and wind power. Renewable energy sources bring their challenges though: when the electricity is produced, it does not necessarily match the demand from the grid. They can be “controllable”, like hydro power for instance, meaning you can adjust the electric power by regulating the water flow, or they can be weather-dependent like solar and wind power with a little control on the electricity generation. If we want to fully exploit their power potential, we need to store the electricity they produce and hydrogen has the biggest potential.

So what are the hydrogen properties that make it so interesting? First of all, it is the most abundant element on earth. It has potential for zero carbon footprints if produced from renewable energy, and it can be transported on long distance. It has a high energy density, actually higher than batteries. Finally, it can serve as a feedstock to capture CO2, to produce methane and other gases. Hydrogen has some very specific characteristics that determine its behavior. It consists of very stable molecules. Whilst hydrogen can burn by itself, it cannot easily detonate, and in the case it does, it has less energy content than other gases, so it is much safer. Since hydrogen molecules are the lightest and smallest they disperse very quickly and doesn't gather in a cloud at floor level like natural gas does. It requires between 4% and 74% oxygen concentration to burn. This means that a hydrogen tank cannot explode, since there is no oxygen present. And when it leaks, hydrogen disappears easily in the surrounding air, as long as it has a way to escape. Hydrogen can be produced in many ways. Most of the hydrogen produced (95%) is obtained from fossil fuels by reforming steam, partial oxidation of methane or gasification of coal. The remaining percentage is reserved for other, less widely used methods such as biomass gasification or water electrolysis. Hydrogen has long history of mass production and usage. It has been used for over two centuries – the first street lighting, for example, used hydrogen. Nowadays, hydrogen is mainly produced for usage in refineries to desulfurize fuels and for the production of ammonia.

In order to make modification in to electric karting, from a classic karting, the gas tank and the gasoline engine were removed, and instead of these components there is a need for deployment electrical components. With the objective of maintaining a similar dynamic performance, the BLDC synchronous electric motor by company Golden Motor [1] was elected, with the power of 5 kW, voltage 48 V and its controller 48 V / 360 A, accelerator pedal and the other components. Drive of electric motor is achieved by Li-Fe-Po battery with 16 cells, a single voltage of 3.2 V, which ultimately provides a total voltage in the range of 44.8 to 51.2 V. In order to symmetry loads, the batteries are arranged on the left and right side of the driver in special carriers, and connected in series to provide a nominal voltage of 48 V. The redesigned karting is given in the Figure 2.

3. HYDROGEN-PROPELLED VEHICLES

Hydrogen is one of the most interesting solutions for propelling the motor vehicles even though, globally speaking, we are still far from using it massively. Many car manufacturers have presented their prototypes and models driven by hydrogen with the aim to emphasize that there is a potential in it. The greatest advantage of hydrogen is the fact that it does not pollute the environment. It does not emit carbon in any form, which also applies to carbon dioxide, nitrogen oxides or particulates. There are two types of hydrogen vehicles: vehicles using hydrogen as direct energy source and vehicles using fuel cells. The former use IC engines modified from standard petrol engines to burn hydrogen. However, the most popular hydrogen vehicles nowadays are the ones using fuels cells.

3.1 Propulsion using hydrogen combustion

Hydrogen can be used in conventional petrol engines as its flame spreads quickly from the ignition core throughout the chamber. However, due to smaller energy density of hydrogen compared to petrol, at pressures suitable for cylinder pistons, engine displacement must be two or even three times bigger than that of petrol engines (around 4 liters and 8 to 12 cylinders are needed), which is a problem in terms of space needed. The comparative overview of some characteristics of hydrogen and petrol is presented in Table 1 [17, 13].

Since large amounts of hydrogen are required to fill larger engine displacement, hydrogen needs to be much denser than it is possible in its gaseous form. Therefore, it is necessary to use liquid hydrogen cooled down to the temperature of around 20 K, as well as special filling stations. Such technologies are already being developed and special tanks for liquid hydrogen have already been designed (with multiple metal cylinders with appropriate insulation). However, it is also necessary to solve the problems of heat dissipation and hydrogen leakage.

Table 1. Comparative overview of certain characteristics of hydrogen and petrol

Characteristic	Hydrogen	Petrol	Unit
Minimum ignition energy in air	0.018	0.2 – 0.3	mJ
Flame temperature	2,207	2,307	°C
Auto ignition temperature	575 – 580	480 – 550	°C
Flame velocity in air ($\lambda = 1$) at 20 °C and atmospheric pressure	2.37	0.12	m/s
Octane number	> 130	90-98	-
Flammability limits in air	4.1 – 75.6	1.48 – 2.3	% of volume

Hydrogen as a vehicle motor fuel is easier to use in public transportation vehicles. The engine and tank size problems are relatively easy to solve in city buses, because of more space is available, including the roof. Hydrogen propulsion using IC engine can be achieved by modifying existing engine in a certain way: valve thermal treatment, installation of non-platinum tip spark plugs, higher coil voltage, injectors designed for gas (not liquid) usage, more durable gasket materials, higher temperature engine oils etc. Many manufacturers have experimented with hydrogen engines. Mazda has developed Wankel engine for hydrogen combustion, an Austrian company named Alset has developed hybrid hydrogen/petrol system for Aston Martin Rapide S which participated in 24 Hours Nürburgring race [19], and BMW has developed their own supercar reaching the speed of 301 km/h burning hydrogen [16].

3.2 Propulsion using fuel cells

The increasingly popular technology widespread with hydrogen cars is the fuel cell technology. The fuel cell converts chemical energy into electric energy with the help of chemical reaction of positively-charged ions of hydrogen with oxygen or another oxidation agent. It is important to distinguish fuel cells from batteries because fuel cells need the flow of fuel and oxygen (air) in order to maintain the chemical reaction and produce electricity. This continuity in the production of electricity, as long as the fuel cell is supplied with fuel and oxygen (air), is its advantage.

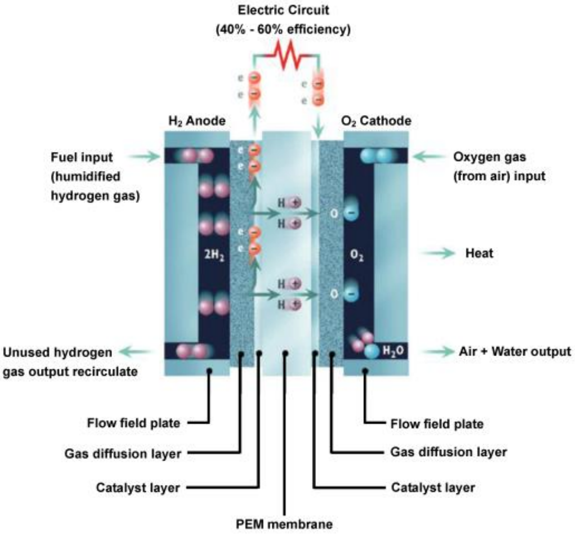

Figure 3. Fuel cell with polymer electrolyte membrane (PEM) - principle of operation

There are many types of fuel cells [7], but the principle of their operation is essentially the same (Fig. 3). Each of them has a cathode, an anode and an electrolyte which enable positively-charged hydrogen ions to flow inside the fuel cell. The cathode and anode have the catalyst which causes the fuel reaction so that it can generate positively-charged ions and electrons. While hydrogen ions flow through the electrolyte after the reaction, electrons flow from the anode to the cathode through the external circuit, thus producing direct current. Fuel cells are mostly classified by the type of used electrolyte and by the time of the reaction initiation, which can vary from one second to several minutes. Besides electricity, fuel cells produce water and heat, as well as the small amount of nitrogen oxides and other emissions depending on the used fuel. In theory, fuel cells would function without losses, but that is not the case in real conditions. During their normal function, the major losses of the fuel cell are: activation losses which directly depend on the degree of the chemical reaction; voltage drop due to the resistance of the medium to the flow of ions and electrons; and concentration losses depending on the reactant concentration and their changes. Theoretical voltage which the fuel cell can achieve is somewhere around 1.2 V. However, due to the energy efficiency of the cell, which ranges from 40% to 60% [29], real operating voltage of the cell is between 0.45 and 0.72 V. Depending on the purpose of the fuel cells, they can be connected in two ways: in series (which produces higher voltage) or in parallel (which produces higher electric current). For the needs of motor vehicles, fuel cells are arranged in a way in which reacting gases must be uniformly distributed in all cells in order to gain maximum power output. The type of electrolyte and its chemical composition determine the type of the fuel cell itself. The fuel it uses is also very important, but pure hydrogen is used most commonly. The anode catalyst, which is usually fine platinum powder, initiates the fuel and dissolves it into electrons and ions. Cathode catalyst, which is most often made of nickel, transforms ions into chemical compounds such as water or, rarely, dioxides of other elements. For the needs of hydrogen vehicle propulsion systems, fuel cells with polymer electrolyte membrane (PEM) represent an optimum choice.

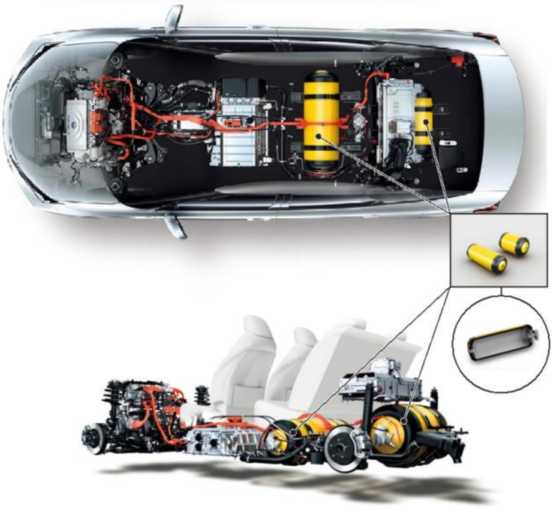

Figure 4. 2015 Toyota Mirai

At this point of hydrogen vehicles development, Toyota has made the greatest progress by presenting the first commercial vehicle propelled by fuel cells at the end of 2014. Toyota Mirai (Figure 4) uses PEM fuel cells – there are 370 of them in the package, arranged in series. One fuel cell is 1.34 mm wide and weights 102 g with the total weight of all cells in the package being 56 kg. The curb weight of the vehicle is 1,850 kg. Increased fuel-cell output voltage enables reduction in the size of the electric motor, as well as in the number of fuel cells. Hydrogen tank refilling takes 3 to 5 minutes, and the vehicle with full tank can cover almost 500 km. This type of vehicle has two tanks made of plastic reinforced with carbon fibers weighing together 88 kg. Fuel cells, arranged in a three-dimensional grid for better dispersion of oxygen, can produce a total maximum power output of 114 kW [1]. Current researches are pointed at making the fuel cells more efficient using advanced control strategies [14, 3].

4. PROBLEMS IN HYDROGEN EXPLOITATION

The main problem is the production of hydrogen, which is estimated to be at least five times more expensive than the production of petrol. The fact that car manufacturers are interested in this technology and its improvement is encouraging, so it is rightfully expected that, in the future, the process of hydrogen production will be significantly cheaper. Another disadvantage is that the hydrogen is separated through the process of electrolysis that needs electricity, which is usually largely produced by environment-unfriendly processes. If the hydrogen is to be the true environment-friendly source of energy, the electricity needed for its production must be produced by environment-friendly processes. Hydrogen storage is also a big problem. There are several ways to store hydrogen and the most popular are compression, liquefaction and storage in underground pits. Hydrogen storage in a liquid state is particularly difficult because it must be carried out in a cryogenic state, or at very low temperatures, since the boiling point is about 20 K (-253 °C). Therefore, the process of liquefaction is a negative energy process, because a large quantity of energy is necessary for the hydrogen to cool down at such a low temperature. Reservoirs must be extremely well protected in order to avoid leakage, and their insulation leads to additional costs.

Compressed hydrogen is stored quite differently. It is known that hydrogen has a good mass energy density, but very low volumetric energy density, especially when compared to hydrocarbons, and therefore a larger storage tank is needed, heavier than the reservoir for conventional fuel for the same amount of energy. Increasing the pressure will increase the volumetric energy density. A high degree of compression without an energy recovery plan will lead to losses in the compression process, so attention should be paid to this factor. Compressed hydrogen may also be exposed to a low permeation rate. For the vehicle's needs, hydrogen is compressed to a pressure between 350 and 700 bar.

The great problem is the infrastructure itself (factories, transport, filling stations). Today, hydrogen is most often transported in compressed or liquid form in containers with gas cylinders. Transport by pipes is also possible, only by land using pipelines used for the transport of natural gas. This would be possible with minimal modifications of existing infrastructure. On the other hand, the construction of a pipeline solely for hydrogen is currently too expensive.

1. FUEL CELL AND BATTERY ELECTRIC VEHICLES COMPARED

The transition to a more sustainable personal transportation sector requires the widespread adoption of electric vehicles powered by batteries (Battery Electric Vehicle - BEV) or fuel cells (Fuel Cell Vehicle - FCV). Automotive manufacturers are now confronted with decisions to invest in technologies that will become adopted in the future. While some manufacturers have chosen to invest in either BEVs or in FCVs, most companies have invested in both and/or have formed partnerships to develop both batteries and fuel cells. Academic literature has not yet sufficiently addressed the battle between BEVs and FCVs [27]. All-electric vehicles, either powered by batteries or by hydrogen fuel cells based on hydrogen produced from renewable energies seem to be the only viable option to meet the future CO2 emission targets of less than 95 of gCO2/km. An analysis of the system-level energy density of lithium-ion batteries (LiBs) suggests that the gravimetric energy density of advanced LiBs is unlikely to exceed 0.25 kWh/kg, which would limit the range of BEVs for the compact car to ca. 200 miles (320 km), with recharging times substantially larger than that of conventional vehicles. Higher energy densities would only be possible, if one were able to develop durable and safe metallic lithium anodes. While the so-called post-LiBs, lithium-air and lithium-sulfur batteries have been assumed to revolutionize battery energy storage, cell- and system-level gravimetric energy densities are not expected to substantially exceed that of advanced LiBs; volumetric energy densities will most definitely be lower. In contrast to BEVs, hydrogen powered FCVs are capable of large driving ranges (more than 480 km) and can be refilled within several minutes. Besides the need for a hydrogen infrastructure based on hydrogen produced from renewable energy, a reduction of the platinum requirement per vehicle (currently ≈20–40 g Pt/FCEV) still requires further development [12]. The importance of technological superiority is confirmed in the literature on the technology battle between BEVs and FCVs. FCVs are considered to suffer from hydrogen storage and safety issues [6,9,15]. BEVs face challenges in range, i.e. battery capacity, and long charging times [2, 21, 23]. These limitations to technological performance make BEVs and FCVs less attractive in the eye of potential buyers, posing a barrier to market acceptance. Batteries are widely used in a wide variety of appliances, whereas fuel cells remain relatively unknown to the broader audience. Batteries are simply a proven technology. Concerning the latter, academic literature [28, 25, 20] indicates many technical specifics that determine superiority of BEVs, ranging from fuel costs and battery/fuel cell life cycle to the performance indicators mentioned above and more advanced factors such as possibilities to use the car for energy storage. An additional consideration worth mentioning at this point is whether technological superiority will remain important. According to Suarez [24], when the first commercial product has been introduced within a product category, technology related factors for standard dominance become less important and marketing and business strategies become increasingly relevant. In other words, once both options have proven themselves in the market, other factors may become more important.

International compatibility is considered critical for the success of BEVs; the difference in charging systems reduces the attractiveness, and therefore, the adoption of BEVs [23,4,18]. The scattered process of development (in time and space) and the current lack of compatibility standards have led car manufacturers to produce vehicles with their own electrical connector types for DC fast charging [30]. In contrast, FCVs hardly have any compatibility issues between FCVs and fuel dispensers as hydrogen dispensing nozzles adapt to car receptacles [26]. Renewable electricity was considered for charging BEVs and the production of hydrogen, but still it’s hard to call FCVs environmentally optimal if they ultimately still waste 78% of the net energy (Fig. 5). Traditional electrolysis has an efficiency of around 70%, whereas a newer technology called proton exchange membrane electrolysis can reach 80%. The transport, storage and distribution of hydrogen cost about 26% of the energy. By contrast, BEVs only have to contend with grid losses, which average around 5%. Once it’s in the vehicle, hydrogen has an efficiency which ranges from 40% to 60% - much better than efficiency of a gas or diesel engine, but lower than the 75% for a BEV. So FCVs are less efficient than BEVs at every stage of the process: generating hydrogen; transportation and storage; and converting it back to energy in the vehicle. In the future, a hydrogen infrastructure is likely to be set up for heavy duty vehicles, and in the shipping and aviation sector, which might enable an easy addition of fuel stations for personal transportation. However, as this infrastructure still needs to be built, and the electricity grid and an increasing number of charging stations are already in place, it is not surprising that experts believe that BEVs still have a substantial advantage over FCVs. In addition, the relative presence of BEVs on the road compared to relatively few FCVs could be responsible for a bias among experts that BEVs have substantially fewer problems related to compatibility.

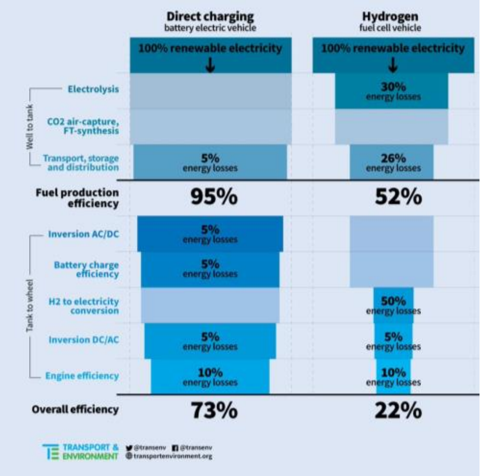

Figure 5. Overall energy efficiency BEV vs. FCV [33]

2. CONCLUSIONS

It should be emphasized that almost all forecasts so far, especially the ones from the end of the previous century, have anticipated a significantly greater usage of electric vehicles in first two decades of 21st century, but that did not happen. The reasons for this may include the existence of the “fossil fuels lobby”, high prices of today’s electric vehicles and undeveloped infrastructure of charging stations. It is clear that future solutions must overcome many obstacles standing in the way of commercialization of hydrogen as a motor fuel. First of all, it implies the reduction of hydrogen production and transport costs, as well as building of a well-spread network of filling stations. Experts anticipate that, despite the presence of certain models, the mass production of hydrogen vehicles will not start in the following 15 years. However, hydrogen, being the most widespread chemical element, is considered a very promising energy source. One interesting advantage is that hydrogen fuel cell technology may have many more uses outside of transportation – the promise of a full hydrogen economy. Fuel cells could power buildings, for example. So hydrogen power may prove more versatile, and its use in transportation may benefit from this, even if by itself it is not inherently better than battery technology. It is also possible that we will end up with both. Some manufacturers are focusing on long-haul vehicles, like trucks, buses, and even trains, propelled by hydrogen. Further, they can build a much more limited infrastructure for predictable travel routes of these vehicles. It seems like car manufacturers are putting most of their resources in battery technology for now, but are hedging their bets by continuing to develop hydrogen fuel cells, which they think will be the long term winner.

ACKNOWLEDGMENTS

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