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ENERGY ANALYSIS OF HYDROGEN USE IN ROAD TRANSPORT OF THE REPUBLIC OF CROATIA

ENERGETSKA ANALIZA UPORABE VODIKA V CESTNEM PROMETU REPUBLIKE HRVAŠKE

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Key words: hydrogen, hydrogen technologies, hydrogen acquisition, transport

Abstract

In this paper, we will calculate the needs for hydrogen if all traffic in Croatia was driven by hydrogen. In the article, we will determine the required amount in several ways. First, we will briefly describe fuel cell cars and the extent to which the amount of exhaust gases would be reduced. We will then explain the ways of obtaining hydrogen, its transport and what the purchase costs would be. Finally, we will compare the results and draw some conclusions.

Povzetek

V članku bomo izračunali, kakšne bi bile potrebe po vodiku, če bi ves promet na Hrvaškem potekal na vodik. V nalogi bomo na različne načine določili potrebno količino vodika, potrebnega za transport na Hrvaškem. Opredili bomo avtomobile na gorivne celice ter količino izpušnih plinov, ki bi se zmanjšala z uporabo vodikovih tehnologij. Pojasnili bomo tudi načine pridobivanja vodika, njegovega transporta in kolikšni bi bili stroški nakupa vozila. Na koncu bomo primerjali rezultate in zapisali ugotovitve.

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1 INTRODUCTION

Road traffic is an indispensable part of everyday life. About 30% of the total energy used and 25% of the total exhaust gas emissions emitted within the EU come from road transport. The European Commission has proposed several different directions for sustainable development, one of which involves the application of hydrogen technology. Regardless of the environmental protection aspect, the need for a new fuel has arisen due to the high prices of currently-available fuels and the dependence on fuel imports. Fuel cells were found as an alternative to internal combustion engines. Since Europe is at a low level of self-sufficiency, its own hydrogen production would help solve an additional problem. Fuel cells are already available on the market and are still under development. Production of fuel cell cars and this technology are also available for purchase, something which represent a very successful development.

2 HYDROGEN CAR

More and more companies are deciding to develop hydrogen cars. The most successful hydrogen car, developed in serial production, is the Toyota Mirai hydrogen car. In Table 1, we present the technical characteristics of the Toyota Mirai car, developed in December 2021. 17,940 units have already been sold, [1] a small number compared to sales of battery electric vehicles, but intense growth in hydrogen vehicle sales has nevertheless been predicted. In Table 1, you can see the technical data relating to the Toyota Mirai hydrogen car.

***Table 1**: Technical data of the car Toyota Mirai [2]*

Motor power	113 kW / 335 Nm
Number of reservoirs	3
Maximum speed	178 km/h
Nominal working pressure	700 bar
Range	550 km (NEDC)
Tank volume	122,4 l
Maximum mass of stored hydrogen	5 kg
Refill time	3 min
Combined consumption	0,76 kg/100 km
Starting price in Germany	60 000 EUR

A fuel cell car has similar design as a battery electric car except instead of a battery it has fuel cells and a hydrogen tank.

The main components of a fuel cell car are:

1. The electric motor;
2. The high pressure hydrogen tank;
3. The battery;
4. The fuel cells;
5. The boost converter;
6. The control unit.

In these cars, hydrogen is stored at 700 bar in three polymer high-pressure tanks. They are made of three layers: an inner plastic layer, a middle carbon fibre plastic layer and an outer plastic layer with glass fibre to protect it against damage. The Toyota Mirai car uses PEMFC or polymer fuel cells where the electrodes are separated by a solid polymer electrolyte. The 650 V electrical installation llows for a smaller number of fuel cells. The battery in fuel cell cars is primarily intended to store excess energy generated during regenerative braking. This stored energy is then used by the car during re-acceleration, thus increasing the car's range. The battery is much smaller than that found in electric vehicles. The size or energy capacity of the Toyota Mirai lithium-ion battery is 1,2 kWh. [1]

Figure 1*: Design of the Toyota Mirai II (https://www.toyota-europe.com/news/2020/new-mirai-concept).*

3 THE NEED FOR HYDROGEN

In this article, we have calculated the energy needs for hydrogen in road traffic of the Republic of Croatia. To determine the required amount of hydrogen for road traffic needs, we calculated the required amount of hydrogen with the help of the data presented in Table 2.

Table 2: *Data required for calculation in Croatia*

Number of registered vehicles	1 666 413 [3]
Energy consumed in traffic	5,34 * 10^{10} *MJ* [4]
Average mileage	15 000 km/year [5]

We calculated the need for hydrogen from the car's declared hydrogen consumption, which was 0.76 kg/100 km: [2]

$$(Consumption_{H_2})_{15000km} = P_{TM} * d = 0{,}76 \frac{kg}{100km} * 15000\ km = 114\ \text{kg} \quad (3.1)$$

Where:

– (Consumption $_{H2}$)$_{15000km}$ – hydrogen consumption (EU average)) – 15 000 km (kg);

– PG_{TM} – Toyota Mirai combined consumption (kg/100 km);

– d – distance (km).

$$m_{H_2} = N * m = 1\ 666\ 413 * 115\ kg = 1{,}92 * 10^8\ \mathrm{kg} \tag{3.2}$$

The electricity required to produce one kilogram of hydrogen is 55 kWh/kg, which means that 6,270 kWh will need to be supplied for one car. It will also be necessary to obtain at least 10,448,409,510 kWh of electricity, which means that a 1,200 MW power plant would be required.

4 HYDROGEN PRODUCTION

As shown in the previous sections, hydrogen is required for a fuel cell car. We already solved the first problem, environmental pollution, by introducing green hydrogen, as opposed to grey and blue hydrogen, both of which are also available. Grey hydrogen, which is currently the most common form of hydrogen, is produced from natural gas or methane in the steam reforming process. Blue hydrogen, on the other hand, is the same as grey hydrogen, except that it captures greenhouse gases in the process. The gas capture process is cost prohibitive. Green hydrogen is created with the help of electricity from renewable sources.

Another problem with conventional fuels is their price. Since we want the lowest possible price and zero pollution, our own local production of hydrogen with the help of renewable sources would represent the most economical solution. Hydrogen can be obtained from fossil fuels and from water. The direction of obtaining hydrogen from fossil fuels is not sustainable from an ecological point of view. Extraction from water can take place via electrolysis, thermochemical and photochemical processes. Currently, only electrolysis devices can be purchased from the above on the market.

Obtaining hydrogen by means of electrolysis can be represented by formula 4.1

$$4H_2O \rightarrow\ 4H_2 + 2O_2 \tag{4.1}$$

As seen in the previous section, a 1200 MW plant is not the best idea. Another option for green electricity is to use photovoltaic systems. The advantage of using photovoltaic panels is the production of DC electricity, which is necessary for electrolysis. In Figure 2, you can see the annual solar radiation.

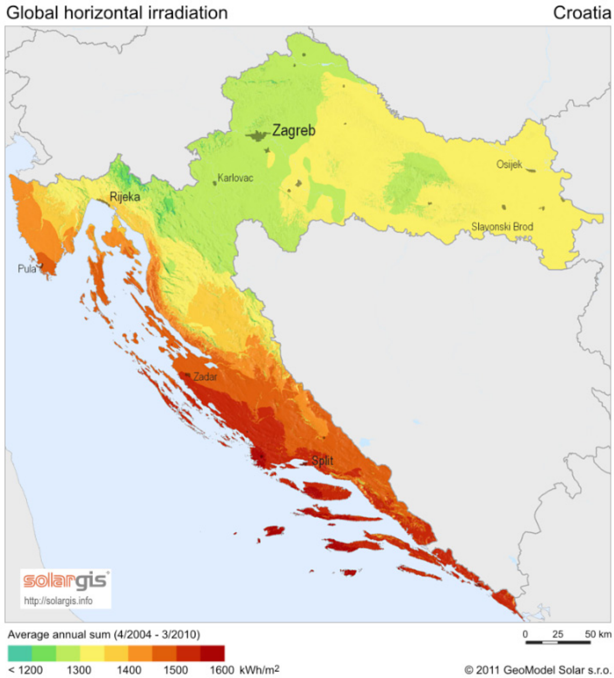

***Figure 2**: Annual solar radiation. [6]*

On average, solar radiation in Croatia amounts to 1250 to 1500 kWh per square metre and 2000 hours of sunshine, [7] which means that our own production of hydrogen could well be something to consider. [6] Currently, the preferred way of producing hydrogen is self-production. If we needed 114 kilograms of hydrogen per car per year, then we would require 6270 kWh of electricity, as well as another 1.35 kWh [8] to compress a kilogram of hydrogen, giving us a total of 6425 kWh. If we, for example, installed 25 photovoltaic modules, each with a power of 300 W, on a roof of 50 m², we would theoretically obtain up to 12000 kWh of electricity per year, which means we would be able to meet these requirements.

$$W_{PV} = W_{modul} * t_{year} * N_{modul} * f = 300\ W * 2000\ ur * 25 * 0{,}8 = 12000\ kWh \quad (4.2)$$

Where:

- W_{PV} – production of photovoltaic modules [W];
- W_{modul} – power of each module [W];
- t_{year} – number of sunny hours per year;
- N_{modul} – number of modules;
- k– correction factor.

As we can see from this calculation, with 25 power modules of 300 W, we can produce enough energy for hydrogen production and compression, allowing us to install fewer modules.

5 REDUCTION OF EMISSIONS IN THE CASE OF SWITCHING TO HYDROGEN

We know from experience that an average car emits between 110 and 150 $\frac{gCO_2}{km}$. Every machine in which a certain fuel is burned produces emissions of certain gases. Car engines have different emissions, which depend mainly on which fuel is used and the engine's fuel consumption. To simplify the calculation, we will use the average consumption. Currently, the most prevalent exhaust gas is carbon dioxide. Data on the amount of CO_2 are as follows. [9]

- 1 litre of gasoline contains 652 g CO_2;
- 1 litre of diesel contains 720 g CO_2.

When we calculate emissions for an average consumption of 5.2 l/100 km for diesel and 7 l/100 km for gasoline, we get:

$$CO_{2,D} = (Consumption_D * CO_{\frac{2}{l},D})/100\ km\ = (5{,}2 * 2640)/100 = 137{,}3\ g/100\ km \tag{5.1}$$

$$CO_{2,B} = (Consumption_B * CO_{\frac{2}{l},B})/100\ km\ = (7 * 2392)/100 = 167{,}44\ g/100\ km \tag{5.2}$$

$$CO_{2,D,15000} = CO_{2,D} * d\ = 137{,}3 \frac{g}{km} * 15000\ km = 2059{,}5\ kg \tag{5.3}$$

$$CO_{2,B,15000} = CO_{2,B} * d = 167{,}44 \frac{g}{km} * 15000\ km = 2511{,}6\ kg \tag{5.4}$$

If we add the average mileage and the average fuel consumption to the above data, with the help of a calculator to calculate the carbon footprint, we obtain the results shown in Table 3: [10]

Table 3: *Total CO_2 emissions*

Fuel	Annual consumption in litres	Annual emissions of CO_2 in kg per 15,000 km	Total annual emission in kg
Diesel	780	2060	1,75 * 10^9 *kg*
Gasoline	1005	2512	2,05 * 10^9 *kg*

If we calculate the average value of 130 $\frac{gCO_2}{km}$ to overall average 15000 kilometres per year, we get the following value:

$$CO_{2,15000} = CO_2 * d\ = 130 \frac{g}{km} * 15000km = 1950\ kg \tag{5.5}$$

We can also calculate this for all cars:

$$CO_2 = CO_{2,15000} * n = 1950\ kg * 1666413 = 3\ 249\ 505\ 350\ kg \tag{5.6}$$

6 PURCHASE COSTS OF HYDROGEN TECHNOLOGIES

In Table 4, we present the price of the Toyota Mirai and its running costs:

Table 4: *Data for Toyota Mirai. [2]*

Car	Toyota Mirai
Propulsion type	Electric motor 113 kW
Fuel consumption	0.76 kg /100 km
CO_2 emissions	0 g/100 km
New vehicle price	60 000 EUR
Annual fuel cost and CO_2 emissions	1083 EUR and 0 kg CO_2

In the Figure 3, we present the costs of several types of vehicles per 15,000 km and the dependence of annual costs on the distance travelled from 5,000 to 100,000 km depending on the type of fuel in Figure 3. [11, 12, 13, 14]

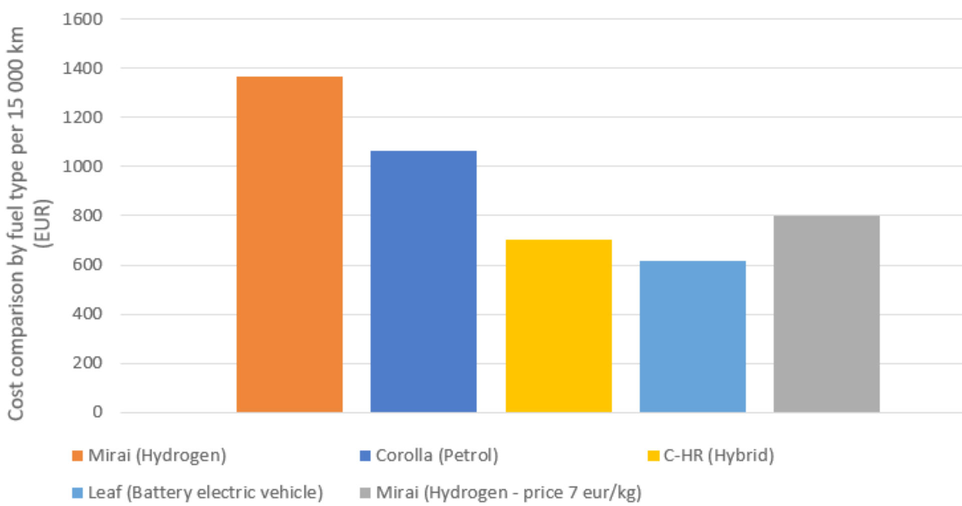

Figure 3: *Annual cost per fuel type per 15,000 km.*

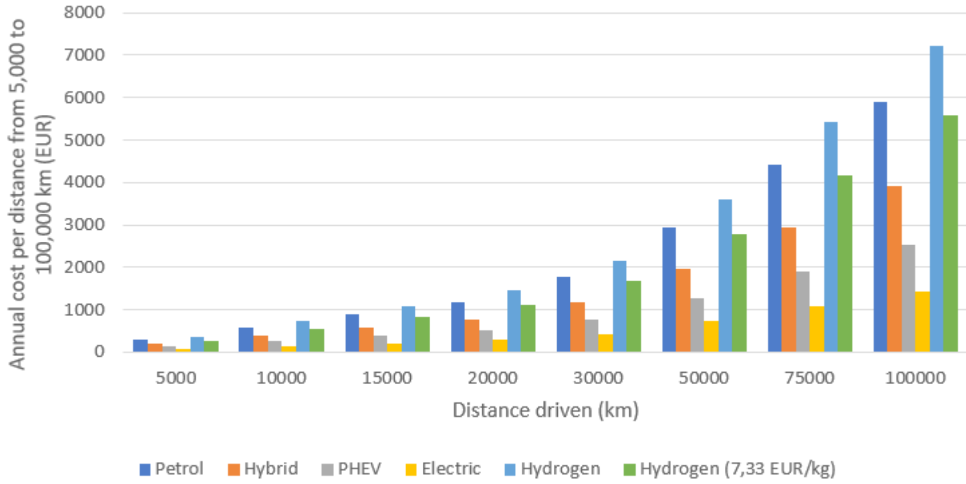

Figure 4: *Annual cost per distance from 5,000 to 100,000 km.*

Figure 4 shows the annual cost per distance from 5,000 to 100,000 km. In a comparison of hydrogen with today's most expensive energy source, gasoline, it can be seen that hydrogen is about 200 euros more expensive per 15,000 kilometres travelled. For every kilometre more, the difference is even greater.

In Figure 5, we can see the price difference depending on the fuel used in the car.

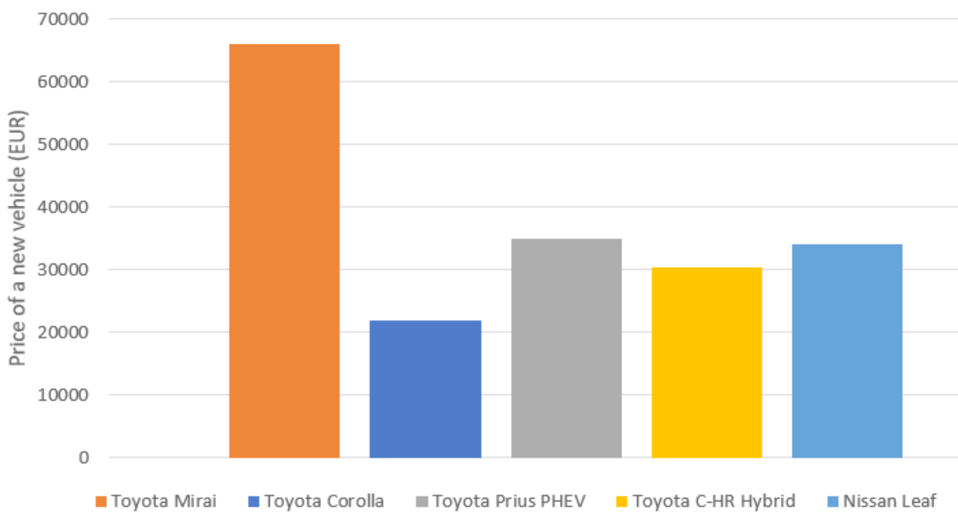

Figure 5: *The price of buying a new vehicle.*

The hydrogen car itself is expensive. The best option at the moment is a hybrid. Therefore, when introducing hydrogen technologies, it will first be necessary to reduce the purchase price of the car. The competitiveness of the hydrogen car could be achieved through subsidies and reductions in car taxes

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Nomenclature

(Symbol)	(the meaning of the symbol)
CO_2	carbon dioxide
P_{TM}	combined consumption of Toyote Mirai
$(\text{Consumption}_{H_2})_{15000km}$	consumption (EU average) – 15 000 km
$CO_{2,D}$	CO_2 emissions of diesel fuel
$CO_{2,B}$	CO_2 emissions of petrol fuel
$CO_{2,D,15000}$	CO_2 emissions for diesel fuel every 15000 kilometers

$CO_{2,B,15000}$	CO_2 emissions for gasoline fuel at 15000 kilometers
k	corection factor
d	distance
$CO_{2,D}^{\bar{l}}$	emissions after burning a litre of diesel fuel
$CO_{2,D}^{\bar{l}}$	emissions after burning a litre of gasoline
H_2	hydrogen
t_{leto}	insolation
W_{modul}	power of each module
N_{modul}	number of modules
O_2	oxygen
W_{PV}	energy production of PV modules