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Energy analysis of hydrogen as a fuel in the Czech Republic

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Abstract. The concept of 'hydrogen economy' dates back to the 1970s. It was first introduced as s response to the first oil crisis. In the context of the hydrogen economy, it is important to calculate how much hydrogen would be needed to power all motor vehicles in the Czech Republic. This is main topics of this paper. To calculate the amount of hydrogen, we used two different methods. One is based on thermodynamic laws and the other on normal operating conditions. Both approaches yielded comparable results. It was found out that even with the use of all the electricity produced in the Czech Republic in 2016, we would not be able to cover the amount of energy that is required for production. It would cover only 75% resp. 76% depending on the calculation method used. Eventually, the Czech Republic could buy necessary amount of hydrogen and it would cost between 11 and 29 billion euros which is between 6% and 16% of GDP of the Czech Republic. In the calculations, authors found out that most fuel is burnt in the passenger cars. Therefore, we made a sensitivity analysis to find out how much our results would differ if fuel consumption changed. It turns out that with an increase in consumption of 1l per 100 km, hydrogen production coverage will decrease by about 4% (again with the use of all electricity produced in the Czech Republic).

Key words: Hydrogen, Alternative fuel, Hydrogen economy, Steam reforming.

INTRODUCTION

Currently, research and development is focused on wider use of alternative fuels to reduce dependence on lowering oil reserves. Conducted research focuses, for example, on fuels made from plant but also on long-known hydrogen (Hönig et al., 2014). It has been considered as a substitute of fossil fuel since the 1970s in response to the first oil crisis (Moliner et al., 2016). Hydrogen as a fuel has minimal impact on the environment, because no CO_2 is produced during combustion. Air and the resulting NO_x emissions can be well controlled through the amount of air supplied to the engine (Cassidy, 1977; Duana et al., 2017).

Its disadvantage is poor storage, inefficient and uneconomical production and the fact that hydrogen compared to fossil fuels is not the primary source of energy. This means that energy needs to be converted first (e.g. in nuclear power plant) and then used for hydrogen production (Vojtěch, 2009).

There is a wide range of processes for producing hydrogen. Briefly, the following methods can be described: electrolysis (decomposition of water into hydrogen and oxygen); thermal decomposition of sulphate; gasification of coal; biochemical processes; steam reforming; partial coal oxidation; biomass pyrolysis; or use of thermolysis. Currently around 48% of hydrogen is produced from natural gas by steam reforming, 30% by oil and 18% by gasification (Abánades, 2012). There are also many new and innovative ways of producing hydrogen. Mainly hydro, geothermal and solar show a unique potential to support these innovative hydrogen production systems (Dincer et al., 2017).

Since steam reforming is the most common form of hydrogen production, the following calculations will account for this form of production. Also, according Ministry of Industry and Trade this method is the most suitable way how to produce hydrogen in Czech Republic (MIT, 2017). Main reactions of steam reforming go according to Eqs (1) and (2).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

Hydrogen can be used as a fuel in two ways: Hydrogen internal combustion engines and fuel cells. Hydrogen burns very quickly, and its flame is stable due to its high calorific value even in the case of a very poor mixture, which can be used to reduce the emissions of nitrogen oxides. The disadvantage of hydrogen combustion is the low volume calorific value of the mixture, given by the low hydrogen density (Doucek et al., 2011; Shivaprasad et al., 2014).

A fuel cell is a device which, in an electrochemical reaction, converts the chemical energy of the continuously fed fuel with the oxidizing agent to the electrical energy. The fuel cell consists essentially of two electrodes and a membrane placed between the electrodes. While there is a reaction between the fuel and the oxidant, electrical charge and heat are formed. Compared to heat engine[1] (Borgnakke et al., 2012) with an electric energy generator, fuel cells produce with 35–50% efficiency, depending on the load and type of fuel cell. The high efficiency is mainly since the energy conversion is direct, not through the intermediate (thermal and mechanical), as in the case of combustion engines (Doucek et al., 2011; Yilmaz et al., 2015; Choongsik et al., 2017).

In the automotive industry, many studies have been undertaken to develop alternative fuel powered vehicles in the last three decades. Advatage of using hydrogen is that it doesn’t produce any carbon dioxide during combustion and it gives significant advantages such as high heating value, short cooling distance, high spreading rate and high flame speed (Gurz et al., 2017).

As of now, there are many mass-produced cars of various brands, such as Toyota Mirai, Hyundai Tucson ix35 Fuel Cell or Honda Clarity. However, other automakers such as Audi, BMW, Toyota or Mercedes also think about the concepts of hydrogen cars. The Strategic Plan for the Use of Hydrogen Technologies KOM (2010) 2020 (Europe 2020: A strategy for smart, sustainable and inclusive growth) has been agreed

[1] Device that operates in a thermodynamic cycle. Convert part of heat into work (Borgnakke et al., 2012).

within the European Union, which helps to define more specific transport and economic development objectives (Soukup, 2017).

Moreover, Czech Hydrogen Technology Platform (HYTEP) opened new period of hydrogen technologies in the Czech Republic. It was established under auspice of the Ministry of Industry and Trade of the Czech Republic. HYTEP has organizes an international conference named Hydrogen Days. The Czech Republic has successfully finalized a series of projects: Tri-HyBus (fuel cell bus prototype), Hydrogen filling station Neratovice, Solid oxide steam electrolyzer (SOSE), Autarkic system. Platinum free novel electrocatalyst, etc., and participated successfully in several European projects (Iordache, 2016).

While there are already many initiatives, it is necessary to focus on the practical aspects of the hydrogen economy. Specifically, the question of how much hydrogen would need to be produced to power all motor vehicles in the Czech Republic needs to be answered.

MATERIALS AND METHODS

There are approximately 7.5 million vehicles on the Czech roads (Sda-cia, 2017). These vehicles were further divided into six groups:

1. Motorcycles – L1;
2. Buses – M3;
3. Passenger cars – M1;
4. Utility vehicles – N1;
5. Trucks – N2, N3;
6. Tractors – T.

From these groups, vehicles with the largest representation in the Czech Republic were selected. These have the greatest impact on the fuel consumption. Since only representatives of a given group are listed, their representation logically does not give 100%.

For this reason, the *Relative Representation* variable – Eq. (1) – was introduced, which recalculates the selected set of vehicles and its sum gives 100%. Other calculations are derived from this value.

$$v_r = \frac{v_i}{\sum_i v_i} \quad (1)$$

where v_r is the relative representation and v_i is the representation of one type of vehicle.

Typical representatives are listed in the tables 1–6 with their average consumption, representation and impact on consumption.

Analyzed motor vehicles

The first group are the motorcycles, which are analyzed in Table 1. On the Czech roads there are 1,108,362 (Sda-cia, 2017). One motorcycle runs for about 15,000 km in a year (CZSO, 2017).

Table 1. Consumption of motorcycles

Type	Consumption L 100 km^{-1}	Representation	Total consumption of fuel L $year^{-1}$
Jawa	5.00	41.2%	$5.5 \cdot 10^8$
ČZ	5.00	7.5%	$1 \cdot 10^8$
Honda	6.00	7.1%	$1.1 \cdot 10^8$
Yamaha	7.00	6%	$1.1 \cdot 10^8$

The second group are the buses (Table 2). On the Czech roads there are 20,645 (Sda-cia, 2017). One bus runs for about 200,000 km a year (CZSO, 2017).

Table 2. Consumption of buses

Type	Consumption L 100 km^{-1}	Representation	Total consumption of fuel L $year^{-1}$
Karosa	32.00	24.5%	$1.3 \cdot 10^8$
SOR	16.00	21.8%	$5.8 \cdot 10^7$
Irisbus	31.00	13.2%	$6.8 \cdot 10^7$
Mercedes-Benz	38.70	8.4%	$5.4 \cdot 10^7$

Another group are passenger cars (Table 3). On the Czech roads there are 5,491,868 (Sda-cia, 2017). One passenger car runs for about 15,000 km a year (CZSO, 2017).

Table 3. Consumption of passenger cars

Type	Consumption L 100 km^{-1}	Representation	Total consumption of fuel L $year^{-1}$
Škoda	7.00	33.7%	$3.5 \cdot 10^9$
Ford	6.00	8.8%	$7.8 \cdot 10^8$
Volkswagen	7.00	7.4%	$7.7 \cdot 10^8$
Renault	8.00	5.8%	$6.9 \cdot 10^8$

Another group are utility cars (Table 4). On the Czech roads there are 554,546 cars (Sda-cia, 2017). One commercial vehicle runs for about 50,000 km in a year (CZSO, 2017).

Table 4. Consumption of utility cars

Type	Consumption L 100 km^{-1}	Representation	Total consumption of fuel L $year^{-1}$
Ford	8.60	14%	$7.1 \cdot 10^8$
Škoda	8.20	12.8%	$6.2 \cdot 10^8$
Volkswagen	8.00	11.8%	$5.6 \cdot 10^8$
Renault	7.80	8.4%	$3.9 \cdot 10^8$

Next group are trucks (Table 5). On the Czech roads there are 189,402 (Sda-cia, 2017). Number of kilometers per year is different for each representative and is therefore listed separately (CZSO, 2017).

Table 5. Consumption of trucks

Type	Consumption L 100 km^{-1}	Representation	km $year^{-1}$	Total consumption of fuel L $year^{-1}$
Avia	16.00	14.2%	50,000	$5.4 \cdot 10^{8}$
Tatra	42.00	8.7%	3,600	$6.3 \cdot 10^{7}$
MAN	36.00	8.5%	125,000	$1.8 \cdot 10^{9}$
Mercedes-Benz	27.00	8.4%	125,000	$1.4 \cdot 10^{9}$

The last group are tractors (Table 6). On Czech roads there are 174,848 (Sda-cia, 2017). Only one representative is listed, as it has a predominant representation over others. One tractor runs for 3,600 km per year (CZSO, 2017).

Table 6. Tractor consumption

Type	Consumption L 100 km^{-1}	Representation	Total consumption of fuel L $year^{-1}$
Zetor	17.50	77.70 %	$1 \cdot 10^{8}$

In addition, it is necessary to distinguish between gasoline and diesel vehicles because these fuels have different energy density – see Table 7 (Andrews et al., 2013; Lukeš et al., 2015).

Table 7. Energy density of individual fuels

Fuel	Energy density MJ L^{-1}
Gasoline	32.18
Diesel	35.86
Hydrogen ($6.9 \cdot 10^{8}$ Pa, 388K)	4.50

For this paper, it has been selected that cars and motorcycles will be powered by gasoline and buses, utility vehicles, trucks and tractors will be powered by diesel. With this assumption, the required volume of fuel from tables 1–6 and calculate the amount of energy ε obtained from the fuels through the energy density can be calculated

$$\varepsilon_i = v_r \cdot N \cdot s \cdot C \cdot \rho \tag{2}$$

where ε_i is required energy for propulsion of vehicles I; N is the number of vehicles i; s is number of kilometers per year per vehicle, C is the consumption and ρ is the energy density.

Then, volume of hydrogen was calculated from energy density of hydrogen and the mass was calculated using the Peng-Robinson's equation (Eqs (3–7) (Peng et al., 1976; Orbey et al., 1998):

$$p = \frac{RT}{V_m - b} - \frac{a}{V_m^2 + 2bV_m - b^2} \tag{3}$$

$$a = 0.45724\,\alpha \frac{R^2 T_c^2}{p_c} \tag{4}$$

$$b = 0.077796 \frac{R T_c}{p_c} \tag{5}$$

$$\alpha = \left[1 + \kappa\left(1 - \sqrt{\frac{T}{T_c}}\right)\right]^2 \quad (6)$$

$$\kappa = 0.37464 + 4.54226\,\omega - 0.26992\,\omega^2 \quad (7)$$

where p is the pressure; R = 8.314 is the universal gas constant; T is the thermodynamic temperature; V_m is the molar volume; T_c is the critical temperature; p_c is the critical pressure and ω is the acentric factor.

Equation parameters for hydrogen are in Table 8 (Orbey et al., 1998).

Table 8. Parameters of Peng-Robinson state equations

Parameter	Value
Critical temperature	33.3 K
Critical pressure	$12.97 \cdot 10^6$ Pa
Acentric factor	-0.215

For the final comparison of the required amount of energy for hydrogen production, the amount of net electricity produced in the Czech Republic in 2016 was used: E_{CZ} = 278,695,080 GJ (ERO, 2017).

The comparison was made in two different ways – empirical and theoretical.

The empirical calculation is based on the amount of energy required to produce hydrogen under normal process conditions: $\Delta H_{r,proc}$ = 2.25 kWh Nm^{-3} (T-Raissi et al., 2004).

The theoretical calculation is based on the application of thermodynamic laws. By computing the reaction enthalpy in the standard state T_1 = 20 °C and subsequent use of Kirchhoff's law, the required reaction enthalpy in the temperature conditions of the steam reforming T_2 = 800 °C – Eq. (8) was calculated. Using the reaction enthalpy, the result with the efficiency of the process 90% was estimated.

$$\Delta H_r(T_2) = \Delta H_r(T_1) + \int_{T_1}^{T_2} C_P(T)\,dT \quad (8)$$

Both calculations will be based on reactions which occur during the steam reforming mentioned in the introduction.

For comparison itself a variable of quantity 'coverage' was introduced. This quantity represents ratio between calculated energy by these two ways and amount of net electricity produced in the Czech Republic. Equation for coverage ratio of empirical calculation is in Eq. (9), equation for coverage ratio of theoretical calculation is in Eq. (10).

$$\Phi_{emp} = \frac{\Delta H_{r,proc} \cdot E_{CZ}}{E_{H_2}} \quad (9)$$

$$\Phi_{theor} = \frac{0.9 \cdot \Delta H_r(T_2) \cdot E_{CZ}}{E_{H_2}} \quad (10)$$

It is also necessary to calculate, what the cost of hydrogen fuel is for the Czech Republic. The price for hydrogen differs according to the methodologies used in other papers. It is not primarily about choosing the right methodology. Rather it is important to cover the potential price range. Prices are found to be in range of (EUR per kg): 2.73

(Demir et al., 2017); 2.84 (Gregorini et al., 2010); 5.04 (Jorgensen et al., 2008); and 7.10 (Gim et al., 2012).

RESULTS AND DISCUSSION

The amount of energy required for propulsion ε_i and the sum of energies, which gives total energy ε are in Table 9. The results show that the biggest amount of energy is consumed in passenger cars and trucks.

Table 9. Energy required to propulsion vehicles

Vehicle	Consumption, L year^{-1}	Energy ε_i, MJ year^{-1}	Contribution to consumption
Motorcycles	$8.83 \cdot 10^8$	$2.84 \cdot 10^{10}$	6.39%
Buses	$3.12 \cdot 10^8$	$1.12 \cdot 10^{10}$	2.52%
Passenger cars	$5.72 \cdot 10^9$	$1.84 \cdot 10^{11}$	41.43%
Utility cars	$2.27 \cdot 10^9$	$8.15 \cdot 10^{10}$	18.34%
Trucks	$3.77 \cdot 10^9$	$1.35 \cdot 10^{11}$	30.43%
Tractors	$1.10 \cdot 10^8$	$3.95 \cdot 10^9$	0.89%
Sum	$1.31 \cdot 10^{10}$	$4.45 \cdot 10^{11}$	100.0%

From the total amount of energy, the required volume and the mass of hydrogen are calculated. The results are $4.09 \cdot 10^9$ kg or $9.88 \cdot 10^7$ m^3 ($6.9 \cdot 10^8$ Pa, 388K).

To compare these enormous figures, a comparison was made with the electricity produced in the Czech Republic. The energy required for hydrogen production was obtained by two different calculations, empirical and theoretical.

Empirical calculation gives $3.07 \cdot 10^9$ kg of hydrogen, which would cover $\Phi = 75\%$. Theoretical calculation gives $3.13 \cdot 10^9$ kg, which would cover $\Phi = 76\%$.

Values are qualitatively the same from both calculations. This is because different procedures are used in the calculations. It can be assumed that the solution approximates closely introduced peculiarities. It is clear from the results that even with the use of all electricity produced in the Czech Republic, it would not be enough to cover all the necessary energy for hydrogen production.

The second way of comparing results is by using the amount of financial funds that would be required to pay for the necessary hydrogen. For the calculations, the minimum, average and maximum prices are used. These numbers are based on aforementioned papers. They are EUR 11.2 billion per year for the minimum price, EUR 18.1 per year for the average price and EUR 29.0 billion per year for the highest price respectively.

In order to compare these calculated numbers with economic peculiarities of the Czech Republic, total Czech GDP is selected. GDP in the Czech Republic in 2016 was 186 billion EUR (Eurostat, 2017). Ratio of required financial funds to GDP are 6%, 9.7% and 15.6% respectively for the lowest, average and highest prices.

It is also necessary to identify main source of these potential costs. Table 9 shows that the biggest energy consumption comes from passenger cars. Therefore, a sensitivity analysis was performed that provides information on how much the coverage would vary when consumption is changed.

The analysis is based on increasing and decreasing fuel consumption (Difference of consumption) of individual vehicles and monitoring of the change of coverage. The result is in Fig. 1.

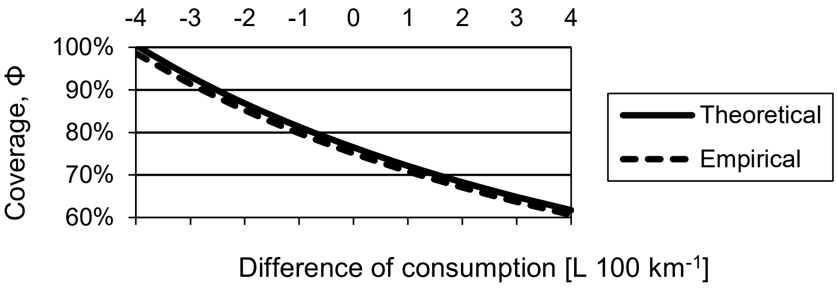

Figure 1. Sensitivity analysis of energy coverage in relation to consumption of passenger cars.

We can see from the Fig. 1 that when the consumption is changed by 1 liter per 100 km, the coverage drops by about 4% in both calculations. Specific numbers are provided in Table 10.

Table 10. Change in coverage depending on the change in consumption of passenger cars

Difference of consumption	Coverage Φ		Difference of coverage	
L 100 km^{-1}	Theoretical	Empirical	Theoretical	Empirical
-3	93%	91%	17%	16%
-2	87%	85%	11%	10%
-1	81%	80%	5%	5%
0	76%	75%	0%	0%
1	72%	71%	-4%	-4%
2	68%	67%	-8%	-8%
3	65%	64%	-11%	-11%

This topic is widely discussed in research papers. For example, Moliner et al., 2016 evaluate the strategy of introducing the hydrogen economy. Their conclusion is that the use of hydrogen should be as a complementary energy source, rather than a competitive one. They propose synergy effects when hydrogen in used the energy mix (Moliner et al., 2016). Other research groups (Iordache et al., 2013; Stygar et al., 2013; Pudukudy et al., 2014) deal with the introduction of the hydrogen economy in individual countries. The main problems identified are the development of energy infrastructure, the petrochemical and agrochemical industries, and the entire production and storage issues. Moreover, the slowing effect of the current geopolitical and economic situation, including the attitude of politicians towards investment in alternative energy sources, has been highlighted.

Besides these scientific papers, there are relatively few articles dealing with the issue of this article – marginally e.g. Liu et al., 2012.

CONCLUSIONS

This paper provides answer to the question how much hydrogen would be needed to power all motor vehicles in the Czech Republic? It is clear from the calculations above that this quantity is currently dramatically higher than the production capacity of the Czech Republic.

Results suggest that using all electricity produced in the Czech Republic wouldn't cover amount of required hydrogen needed. Alternatively, the Czech Republic could buy all hydrogen and it would cost up to 15.6% of GDP of the Czech Republic.

It was also found out that most of the energy is consumed in passenger cars. A sensitivity analysis was provided in the paper. Analysis shows that the increase of consumption by 1 liter per 100 km would increase the amount required hydrogen by about 4%.

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