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LIFE CYCLE ASSESSMENT OF FUEL CELLS ELECTRIC VEHICLES

Summary. In recent years, regarding the influence of the production processes and vehicles on the environment, new technical solutions for reducing air pollutions have been studied and developed. One of the new constructions is fuel cell electric vehicle (FCEV). The production and running conditions of the vehicles are specific in different countries. Hence, a study of these conditions and fuel production process is needed. In this paper, a study of the FCEV efficiency, at different producing technologies of hydrogen (H_2), is carried out. Life cycle assessment (LCA) method is used. A comparison, concerning fuel consumption and emissions as CO_2 equivalent for the whole life cycle, is done for FCEV and conventional gasoline vehicle (GV). The influence of the energy mix and technology of production of hydrogen on spent energy and air pollution is analyzed. As the results show, in countries with CO_2 emissions over 447 g per 1 kWh electricity, the technology of hydrogen production from natural gas is most effective. Now and in the near future, the ecological and financial advantages, connected to renovation of existing vehicle fleet with FCEV, are not absolutely verified.

1. INTRODUCTION

During the past decade, life cycle assessment (LCA) has become a dominant methodology in research studies concerning sustainable development of a product [14]. LCA is applicable also for studying the influence of a production process on the environment. Existing research studies [2, 18, 26, 29, 21] about the effectiveness of fuel production and use in vehicles stimulate environment protection and support development in this area.

Production and use of FCEV as an alternative to conventional vehicles require an assessment of their advantages and disadvantages for the life cycle. FCEVs, like battery electric vehicles (BEV), do not generate air pollutions during the motion process. The main difference between these two types of vehicles is supply sources for the electric motor with electric energy. In FCEV, the electricity is produced in motion, from fuel cells (FC), by continuous supply of hydrogen (H_2) and oxygen (O_2). Produced electricity is used not only for motion but also for charging the electric battery at some regimes.

The fuel cell is an energy convertor, with a theoretical efficiency up to ≈ 83% [7]. If all losses in auxiliary systems of the cell are taken into account, the real efficiency of electric vehicle fuel cells is approximately 40-50 %. This value is nearly as efficient as the diesel ICE [7].

The main properties of the gasoline, natural gas, and hydrogen are presented in tab. 1.

The gasoline is produced at normal atmosphere conditions through distillation of crude oil at temperature from 30 to 200^o C. The main stages of the process are shown in Fig. 2.

The maximal and minimal values of the specific burning heat of coal are accepted respectively as 25.86 and 27.16 *MJ/kg.*

There are three basic methods for hydrogen production [1, 2]: reforming of natural gas, gasification of coal, and electrolysis of water (Fig. 1). In the last decade, production of H_2 from biomass has increased. It is generated by the industry and farms. Electrolysis through solid oxides electrodes (SOEC) is one possibility to produce hydrogen using renewable energy sources. The properties of the basic technologies are summarized in Tab. 2.

Table 1

Physical-mechanical properties of the regarded vehicle's fuels

	Gasoline	**Natural gas**	**Hydrogen**
Chemical formula	C_8H_{17}	CH_4	H_2
Specific burning heat, (LHV – HHV), MJ/kg	43,45 – 46,54	45,86 – 50,84	119,95 – 141,88
Energy density, (LHV – HHV), MJ/l	33,16 – 34,90	$(35{,}22 – 39{,}05)10^{-3}$	0,1 MPa – $(10{,}05 – 11{,}88)10^{-3}$ 35 MPa – (2,837 – 3,355) 70 MPa – (4,761 – 5,631) liquid – (8,685 – 10,273)
Density at 20° C, kg/l	0,72 – 0,76	$0{,}7166.10^{-3}$	0,1 MPa – $0{,}0838.10^{-3}$ 35 MPa – $23{,}65.10^{-3}$ 70 MPa – $39{,}69.10^{-3}$ liquid – $72{,}41.10^{-3}$

*LHV, HHV – respectively low and high limit of the value

Table 2

Needed resources and generated emissions for production of 1 *kg* H_2 using different sources and technologies [1, 2]

Method	**Thermo-chemical**				**Electrolysis**	
Raw materials	Reforming of natural gas with steam	Gasification of coal	Gasification of biomass	Reforming of biomass	PEM	SOEC
Natural gas, kWh	45,833	–	1,73	–	–	14,1
Coal, kg	–	7,8	–	–	–	–
Biomass, kg	–	–	13,5	6,54	–	–
Electricity, kWh	1,11	1,72	0,98	0,49	54,6	36,14
Water, kg	21,869	2,91	305,5	30,96	18,4	9,1
Average CO_2 emissions, kg*	12,13	24,2	2,67	9,193-14,02	29,54	23,32

* Based on EU-28 mix

2. RESEARCH METHODOLOGY

The used LCA takes into account all processes, connected with the product (in our case fuel) – from extraction of raw material, production process, use in vehicles, and it recycling (eventually) [14]. Schematic, the LCA for hydrogen and gasoline is presented in Fig. 1 and Fig. 2. The recycling includes all facilities used in the process.

In the conduction of energy analysis, the maximal value of specific burning heat (HHV) is used (Tab. 1). It corresponds better with real energy content of the fuel, based on the principal of energy saving.

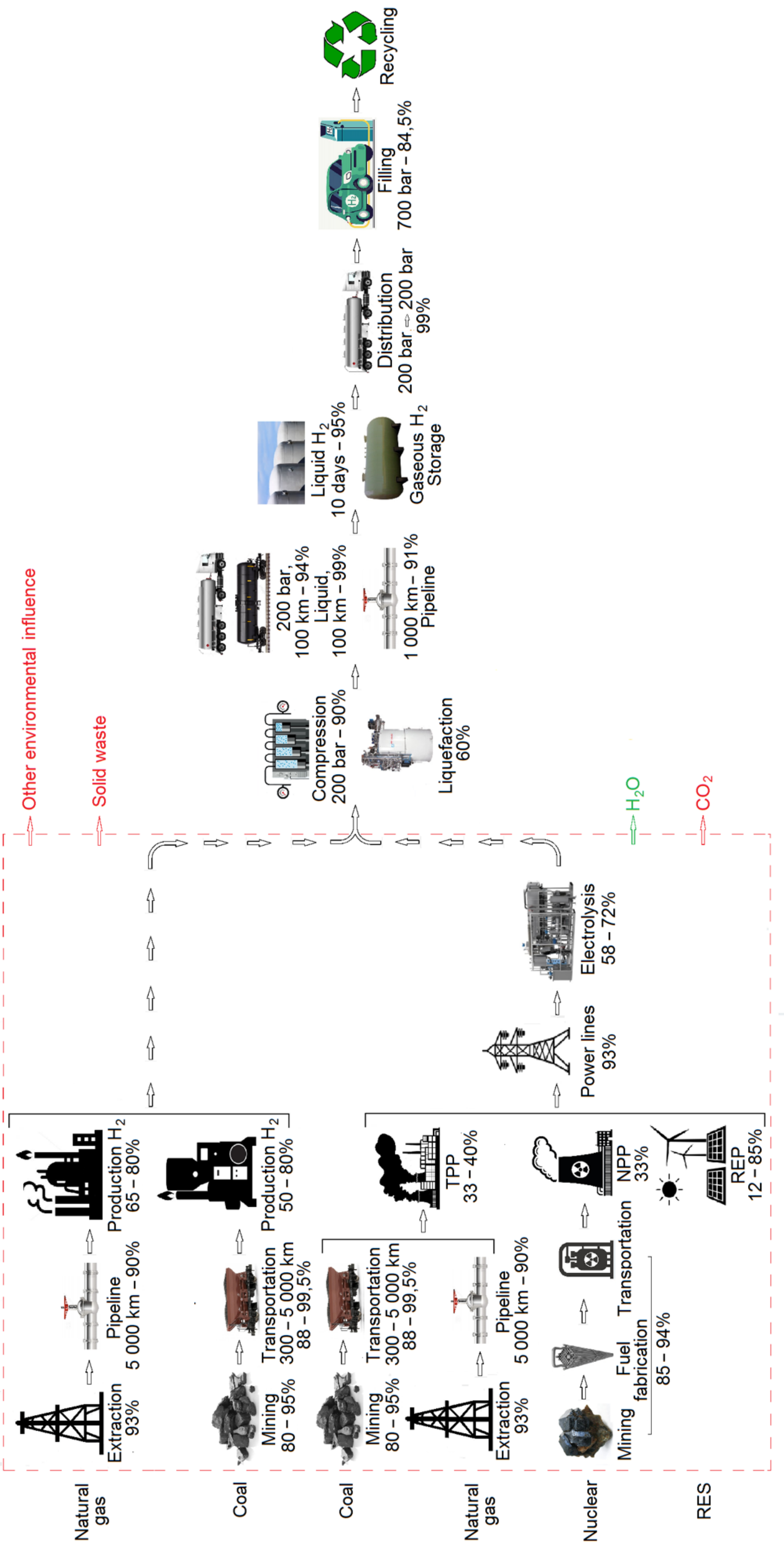

Fig. 1. LCA diagram for production and use of hydrogen in FCEV

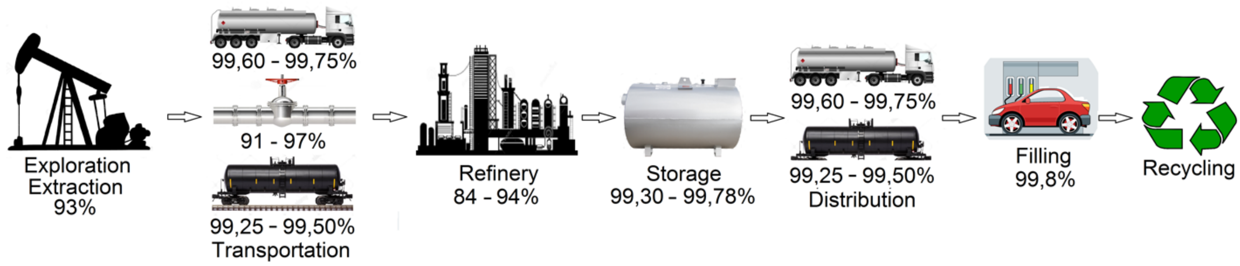

Fig. 2. LCA diagram for production and use of gasoline in GV

The needed primary energy is analyzed only concerning production of H_2 and its compression up to 700 bar or its condensation. The same also concerns the environmental estimation.

A comparison between structure of FCEV (Fig. 3) and conventional GV shows that they have one similar part of construction – chassis, which includes steering system, brake system, suspension, and body. Nevertheless, propulsion system and its components are very different, and for its production, the spent energy and generated emissions will be different values. Usually, the FCEV has approximately 20% bigger mass.

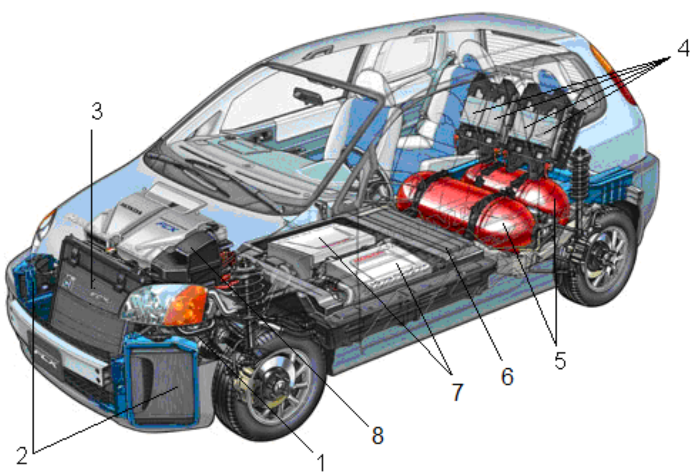

Fig. 3. Structure of a fuel cells electric vehicle: 1 – electric motor; 2, 3 – cooling system for transmission and FC; 4 – supercondensors; 5 – reservoirs with fuel (hydrogen); 6 – moisture device for FC; 7 – blocs of FC; 8 – power electronics

In this study, it is assumed that energy spent for production of chassis of FCEV and GV is equal and consists of 11900 *kWh* [19].

For production of the FC and its management systems, the spent energy is approximately 15% more than for chassis of vehicles [24]. For this reason, it can be accepted that production of the FCEV uses 80% more energy and generates 80% more emissions than production of a GV. However, 100% of GV parts can be recycled, but for FC, this percentage is only 75% [24, 33].

When the needed primary electric energy for vehicle production is determined, the structure of country energy mix is considered (Tab. 3). The efficiency of the used technologies for electricity production is also taken into consideration [11].

Table 3

Structure of the electric energy production (mix) of
the EU-28 countries and Norway [11, 27] in 2015 year

Country	Share of total production, %				
	Nuclear energy	Thermal power-plant			Renewable energy
		Solid fuels	Natural gas	Crude oil	
Austria	0,0	0,0	8,7	7,3	78,0
Belgium	65,0	0,0	0,0	0,0	28,5
Bulgaria	33,2	48,7	0,7	0,2	17,0
Croatia	0,0	0,0	33,5	15,6	50,7
Cyprus	0,0	0,0	0,0	0,0	97,4
Czech Republic	24,2	58,6	0,7	0,7	14,9
Denmark	0,0	0,0	26,4	48,7	22,5
Estonia	0,0	75,6	0,0	0,0	23,2
Finland	34,2	4,8	0,0	0,4	59,3
France	82,5	0,0	0,0	0,8	15,7
Germany	19,8	35,9	5,3	3,0	32,5
Greece	0,0	67,0	0,1	0,7	31,2
Hungary	36,7	13,6	12,2	7,6	29,0
Ireland	0,0	39,8	5,6	0,0	51,3
Italy	0,0	0,1	15,3	16,1	65,2
Latvia	0,0	0,0	0,0	0,0	99,6
Lithuania	0,0	1,3	0,0	4,8	92,5
Luxembourg	0,0	0,0	0,0	0,0	76,9
Malta	0,0	0,0	0,0	0,0	100,0
Netherlands	2,2	0,0	82,0	4,3	10,1
Poland	0,0	79,6	5,5	1,4	12,8
Portugal	0,0	0,0	0,0	0,0	97,7
Romania	11,3	17,7	33,0	15,6	22,3
Slovakia	62,6	7,8	1,2	0,2	25,2
Slovenia	43,0	25,4	0,1	0,0	30,2
Spain	44,2	3,7	0,2	0,7	50,5
Sweden	43,2	0,3	0,0	0,0	54,6
United Kingdom	15,3	4,3	30,1	39,3	10,0
EU-28	**28,9**	**18,9**	**14,0**	**9,8**	**26,7**
Norway	0,0	1,4	0,0	0,0	98,6

The fuel consumption is determined on the basis of HHV of H_2 and gasoline, as well as efficiency of the ICE and FC. That way, equal energy is used for motion of the two type of vehicles with equal mass. Determination of the energy spent during exploitation of the GV and the losses concerning life cycle of the fuel are calculated, and this way the efficiency of gasoline production is evaluated as 79.6% [11, 23, 28]. Considering the expected trends in development of FC production technologies, a value of FC efficiency of 50% [4] is used in calculations.

The generated CO_2 emissions during the exploitation period of the two types of vehicles are determined on the basis of average fuel consumption. Evaluation of the generated CO_2 emissions during vehicles life cycle is done, taking into account emissions per 1 *kWh* electric energy consumption (Tab. 4) in vehicle production process, at the respective voltage (HV or LV) [1].

Based on the conducted literature observation, the following values of power-plant (PP) efficiency are accepted: nuclear PP – 29.5% [3]; Thermal PP with coal – 26% [6]; Thermal PP with natural gas – 40%; water PS (power station) – 60% [16]; wind PP – 40%; average efficiency for renewable energy sources PP – 50%; and losses for transfer and distribution of electricity – 5%.

Table 4

Emissions of CO_2 in the production of electricity for
EU-28 Member States [11] and Norway [34], *g/kWh,* in 2015

Country	Gross electricity production (combustion only)	Gross electricity production (with upstream)	Net electricity production (with upstream)	Electricity consumed at HV (with upstream)	Electricity consumed at LV (with upstream)
Austria	133	151	156	322	334
Belgium	188	224	233	261	267
Bulgaria	507	532	585	618	669
Croatia	231	273	282	487	524
Cyprus	646	737	773	787	810
Czech Republic	518	545	587	657	685
Denmark	316	368	386	364	377
Estonia	1020	1022	1152	878	944
Finland	171	200	209	207	211
France	66	88	92	100	105
Germany	485	534	567	599	615
Greece	655	695	755	732	767
Hungary	310	340	368	383	407
Ireland	459	533	555	588	617
Italy	358	427	444	413	431
Latvia	134	173	185	1110	1168
Lithuania	204	246	262	370	390
Luxembourg	236	288	283	508	513
Malta	731	831	868	954	1032
Netherlands	479	559	582	555	569
Poland	770	847	929	937	980
Portugal	295	346	355	372	400
Romania	356	379	413	449	492
Slovakia	173	199	211	412	420
Slovenia	315	329	351	309	321
Spain	248	295	305	321	341
Sweden	16	24	25	45	47
United Kingdom	469	555	584	593	623
EU-28	**340**	**387**	**407**	**428**	**447**
Norway	–	–	–	–	17

In the present investigation, the following assumptions based on the literature are accepted: equal mass of the FCEV and GV; fuel consumption of the GV – 7,6*l*/100 *km*; range for the life cycle of the vehicles – 290 000 *km*; and hydrogen consumption of the FCEV, determined on the basis of average data for modern FCEV - 1,07 *kg/100 km*.

Table 5

Main technical data of some modern FCEV

Model / Technical indicators	 2017 Honda Clarity	 2017 Hyundai Tucson	 2017 Toyota Mirai
Consumption of H_2, kg/100 km: – urban; – inter-city; – combined.	 0,914 0,942 0,928	 1,295 1,243 1,268	 0,942 0,942 0,942
Electric motor	PMSM, 130 kW	ASM, 100 kW	ASM, 56 kW
Battery	Li-ion, 346 V	Li-ion, 180 V	NiMH, 245 V

3. ANALYSIS OF THE EXISTING TECHNOLOGIES FOR PRODUCTION, STORAGE, AND TRANSPORTATION OF HYDROGEN AND GASOLINE

The global annual production of H_2 is more than 50 million tones. The main part of whole production is from natural gas – 48%, from refinery waste gasses – 30%, from coal – 18%, and other 4% from biomass and through electrolysis [2].

Efficiency of hydrogen production from natural gas is between 65% and 80% [13, 17, 21, 23, 30]. The CO_2 emissions per 1 *kg* H_2 are 9,066-10,728 *g*. On the basis of HHV values of natural gas and hydrogen (Tab. 1), and taking into account technological losses, it is evaluated that for production of 1 *kg* H_2 the needed natural gas is 3,17 *kg*. For the life cycle of FCEV, production of the hydrogen will use 9 840 *kg* natural gas and 3 450 *kWh* electric energy. Production of 1 *kg* H_2 , using EU -28 mix, generates 12,13 *kg* CO_2 emissions (Tab. 2), or for life cycle of the FCEV, the mass of the emissions will consist approximately of 37 640 *kg*.

Effectiveness of hydrogen production from coal varies between 50% and 80% [9, 30], depending on technology and quality of used coal. The losses in production of coal are 5-20%, depending on exploitation conditions and place of the mine [3, 5], and losses for transportation can reach up to 15% [20]. Hence, for life cycle of FCEV, production of hydrogen from coal, a value of effectiveness of 50% can be used [23]. The mass of the CO_2 emissions consists of 24,2 *kg* per 1 *kg* H_2 [2].

Production of H_2 from biomass will have important place in the future, because it is a renewable source. Effectiveness of hydrogen production through gasification of dry biomass (like wood, straw etc.) is into the limits of 65,7-79,1%. Generated CO_2 emissions are up to 13,5 *g* per 1 *kg* H_2. The wet waste from biomass (like sediments, organic waste etc.) can be put to gasification (effectiveness of 35.8-40.3%) or bio-chemical treatment (effectiveness of 29.1-36.3%) [22]. Generally, the effectiveness of hydrogen production from biomass is accepted as 65.7% [22].

Production of hydrogen through electrolysis has effectiveness of 47-82% [8, 26, 30, 31]. High values concern modern electrolyzers. Without losses for transfer of the electricity ($\approx$ 5%), the efficiency is 68.4%.

Alkali electrolysis is known and used since the 18th century. It is in the basis of technology and more of commercial electrolyzers. The produced hydrogen is very pure, but the price is higher because of low price of petrol (used in SMR) in comparison with electricity. Low-temperature polymer electrolyte membrane (PEM) and high-temperature electrolyzers of solid oxides (SOE) are two more effective future technologies. PEM is appropriate for production of small volumes of hydrogen. SOE electrolyzers can reduce consumption of electricity using thermal cracking process [5, 25].

The use of RES for supply industrial electrolysis [15] is very small – about 3%. The main cause is low efficiency.

With electricity from photovoltaic power-plant in technology with efficiency of 10-25% will give a total efficiency of electrolysis from 7.8 to 18% [32]. With the same technology using electricity from solar PS and Sterling motor and generator, the total efficiency can be increased to 28% [32].

Solar PS using cycle of Rankine and technology of solar tower can achieve annual efficiency of 15% and total efficiency of electrolysis of 14% [32]. The solar PS with parabolic reflectors has annual efficiency of 12%, and total efficiency of transformation process of solar energy into hydrogen using electrolysis is 11% [32].

Transportation of the hydrogen is realized by pipes or in special tanks (as gas or as liquid) using vehicles and railway or marine transport. The cheapest method for large volumes of H_2 is transportation as gas in pipes. The losses during transportation of hydrogen are significantly higher than analog losses for natural gas, because of short distance between the compression stations [35, 36].

Charging of the hydrogen on FCEV is made in special hydrogen stations at pressure 700 bar (70 MPa). Usually one charge is enough for a range of 400-500 *km*.

Compression of the hydrogen needs about 3.5 times more energy [35, 36] in comparison with natural gas at same pressure (Fig. 4).

Fig. 5 shows a possibility for reducing the transport losses – if the hydrogen is liquid [36]. The transformation process of H_2 in liquid phase generates losses up to 40% [12, 36]. In analysis done below are used values for losses equal to 15.5% (from HHV) for compression up to 700 bar and 33.33% for transformation process of H_2 in liquid phase.

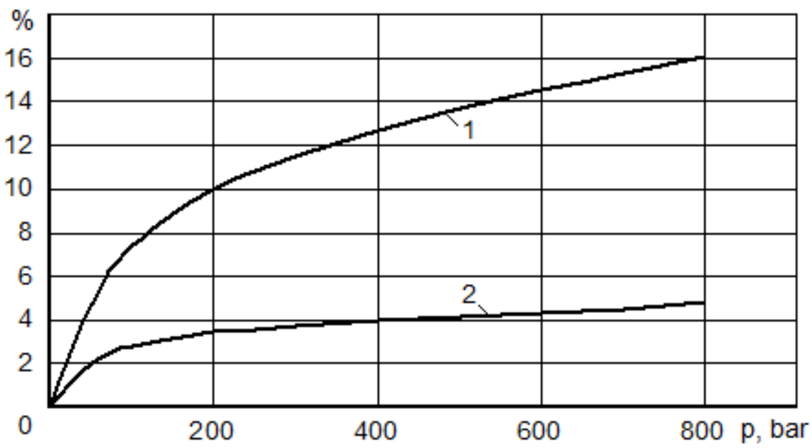

Fig. 4. Relation between energy losses for compression (in % of HHV) and pressure p: 1 – for H_2; 2 – for CH_4

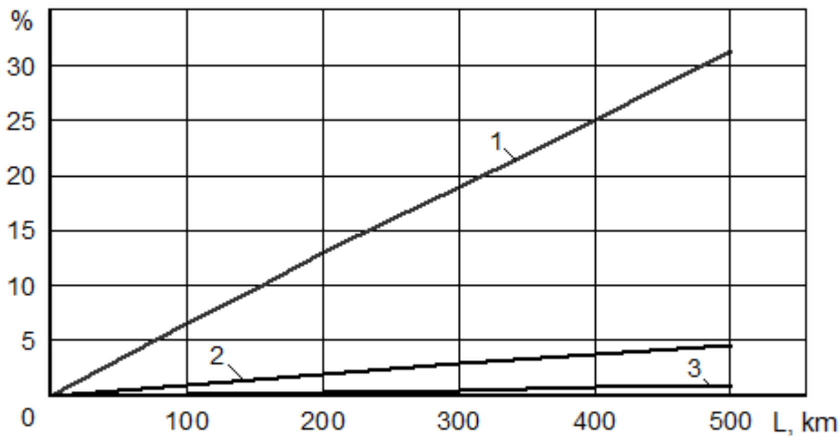

Fig. 5. Relation between energy losses for fuel transportation by vehicle (in % of HHV) and transport distance L: 1 – gaseous H_2 (at 200 bar); 2 – liquid H_2; 3 – gasoline

Transportation of H_2 in pipe generates less energy losses. Transportation of natural gas at a distance of 5 000 *км* generates losses of 10% (Fig. 6). For H_2 transport losses are 35%, because of energy spent for supply of the compressors, placed at each 150 *км* (generated losses of about 1.4%) [36].

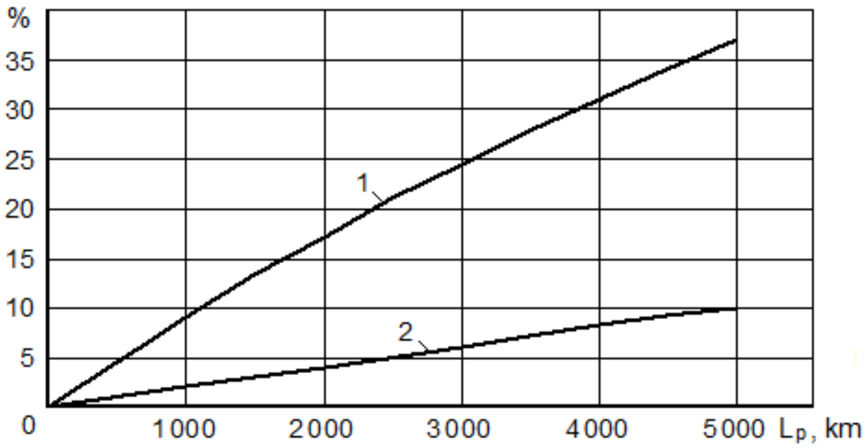

Fig. 6. Relation between energy losses for fuel transportation in pipe (in % of HHV) and transport distance L_P: 1 – for H_2; 2 – for CH_4

Storage of liquid H_2 generates the highest losses – 5.5 *kg* per day for a reservoir of 725 *kg* capacity, which is 0.76% per day [10]. There is a tendency in future to decrease storage losses to 5% per 10 days.

4. LCA FOR FCEV AND GV. RESULTS AND ANALYSIS

Using the aforementioned given information, an assessment of constant energy losses and generated emissions for FCEV and GV was done. Following diagrams from Fig. 1 and 2, the two models were described – for FCEV and GV. The primary energy spent for the life cycle of the FCEV was evaluated by the following model

$$E_P = \frac{1}{\eta_T} \sum_{i=1}^{n} \frac{\alpha_i}{\eta_i} \left(E_{MV} + E_{PH_2} + E_{C(L)H_2} \right),\ kWh \tag{1}$$

where α_i is the part of electricity produced in different types of power-plants (as part of whole produced energy); η_T – efficiency of electricity transfer; η_i – efficiency of different power-plants, including production technology and fuel transportation; E_{MV} – energy spent for production and recycling of the vehicle, *kWh*; E_{PH_2} – energy spent for production of H_2 for life cycle of FCEV, kWh; $E_{C(L)H_2}$ – energy spent for compression or transformation in liquid phase of H_2, *kWh*.

The generated emissions were evaluated by the expression

$$CO_2\ emissions = c \left(E_{MV} + E_{PH_2} + E_{C(L)H_2} \right) 10^{-3},\ kg \tag{2}$$

where c is emission factor for production of electricity, g / kWh (see last column in tab.4).

For GV, used equations are as follows:

$$E_P = \frac{1}{\eta_T} \sum_{i=1}^{n} \frac{\alpha_i}{\eta_i} \left(E_{MV} + E_{PG} \right),\ kWh \tag{3}$$

where E_{PG} is energy spent for production of gasoline for life cycle of GV, kWh ;

$$CO_2\ emissions = \left[c \left(E_{MV} + E_{PG} \right) + eL \right] 10^{-3},\ kg \tag{4}$$

where e is average specific value of CO_2 emissions caused by driving, g/km (used value 180 *g/km*), and L – range of GV for life cycle, *km* (used value 290 000 *km*). An LCA of FCEV and GV concerning needed primary energy and emissions was done by models (1) and (2). The calculations were repeated 4 times – for conditions in Bulgaria, Poland, Norway, and corresponding to energy mix of EU-28. The results are presented on Fig. 7 and 8 and also in Tab. 6 and 7.

The technology for production of hydrogen from natural gas is most effective by criterion of spent primary energy. Using it, at some conditions, FCEV can be a competitor of GV. The technology of production of H_2 from coal and by electrolysis, at the current stage of development, is less effective concerning primary energy for life cycle of GV vehicle. Significant use of the RES in energy mix of the country can give advantage of the FCEV – for example Norway (Fig. 7).

By criterion emissions, the technology using natural gas for production of hydrogen has advantage once again. At the moment, other technologies are less ecological and their use less ecological in comparison with GV. Only in Norway, thanks to the large use of the RES in energy mix, the FCEV is more ecological. Energy mix, including basically thermal PS on coal, is a factor for bigger losses of energy during life cycle of the FCEV and more CO_2 emissions – for example Poland and Bulgaria (Fig. 7 and 8).

One better assessment of the three used technologies for production of hydrogen can be done on the basis of needed primary energy (Fig. 9) and generated emissions in CO_2 equivalent per 1 *km* (Fig. 10).

For the life cycle of the GV are spent 309 750 *kWh* or 1,068 *kWh/km* at accepted range of 290 000 *km*. By this criterion, FCEV is a competitor to GV only in case of using compressed hydrogen. In Norway, FCEV is more effective as it consumes less primary energy –15.5 and 25% for liquid and compressed H_2, respectively. The electrolysis is the worst of the three technologies. The energy spent for life cycle of the FCEV, depending on energy mix of the country, can be over 2.5 times higher than respective for GV. For the life cycle of GV are generated 59 750 *kg* CO_2 emissions or 0,206 *kg/km.*

Results (Tab. 7) show that the best ecological technology is electrolysis for countries using a large part of RES in its energy mix. For example, in Norway, FCEV will have 16 times less emissions (Fig. 8). The structure of energy mix has the most significant influence on production of hydrogen through electrolysis in countries with high level of emissions per 1 kWh electricity. Most ecological for these countries is technology for production of H_2 from natural gas. Produced and used in these countries, FCEV will have ecological disadvantages in comparison with GV, independent of used technology for production of hydrogen (Fig. 8).

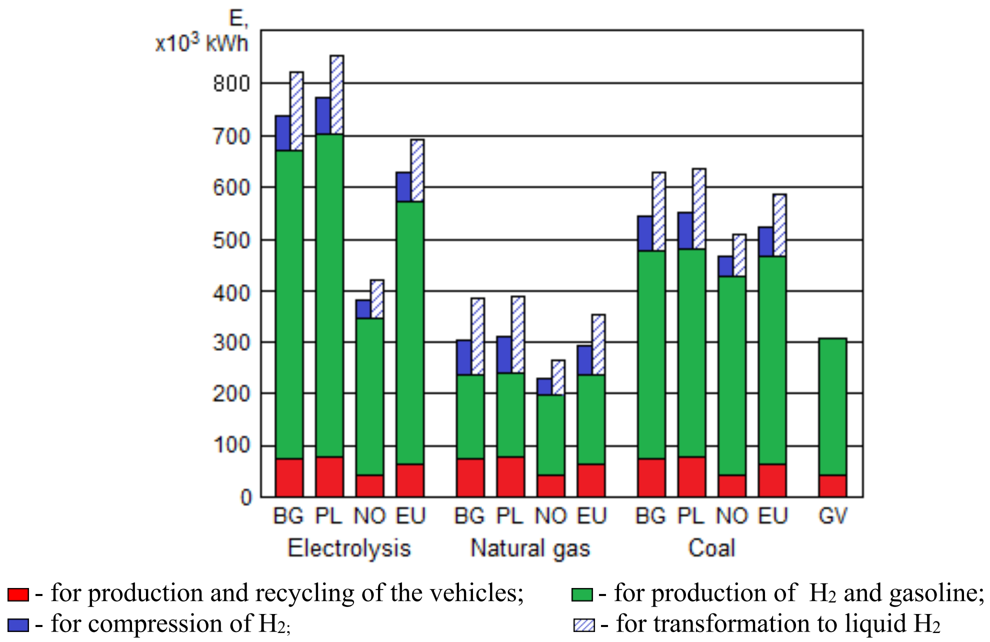

Fig. 7. Primary energy, spent for life cycle of the FCEV and GV

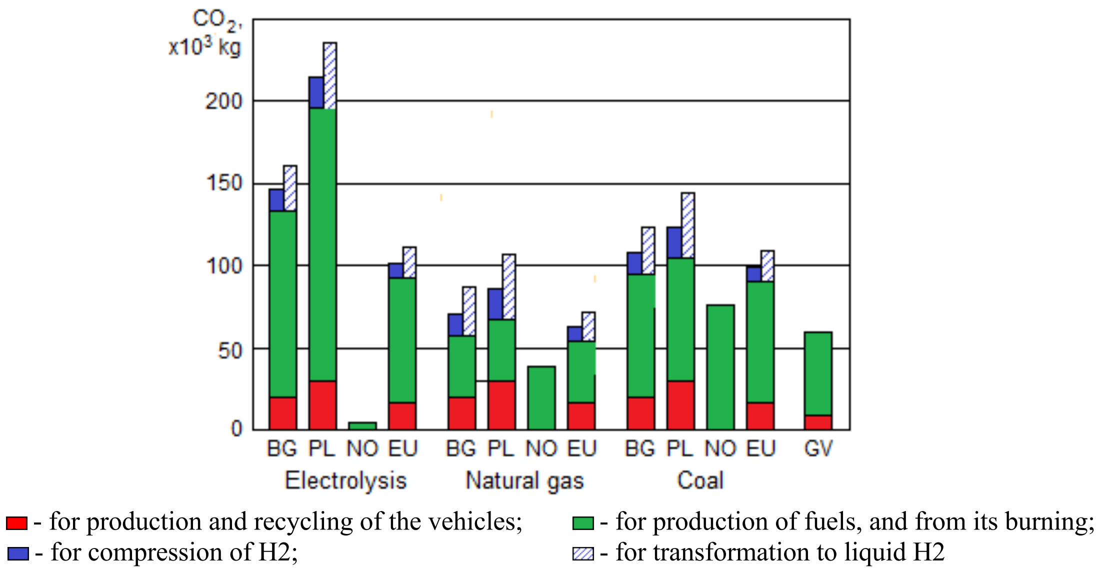

Fig. 8. CO_2 emissions generated for life cycle of the FCEV and GV

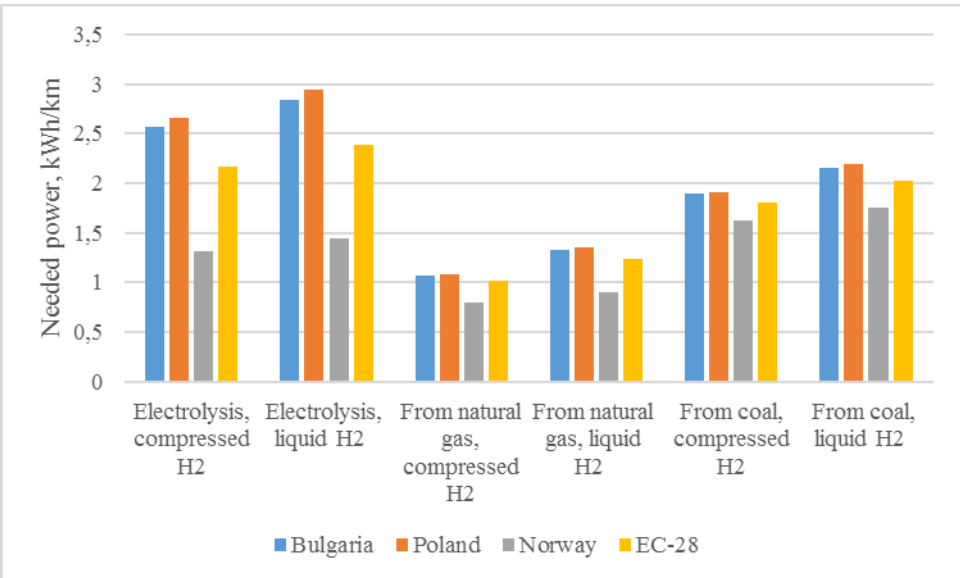

Fig. 9. Needed primary energy in *kWh/km* concerning different technologies for production of H_2

5. CONCLUSIONS

In this paper, a study of the FCEV effectiveness, at different producing technologies of hydrogen (H_2) was carried out. Using life cycle assessment, a comparison, concerning energy consumption and air pollutions for fuel cell electric vehicle and conventional gasoline vehicle, was done. The influence of the energy mix and technology of production of hydrogen on spent energy and air pollution was analyzed on the basis of statistical data.

The obtained results show that the technology of hydrogen production from natural gas is most effective in countries with CO_2 emissions over 447 g per 1 kWh electricity.

The energy spent for life cycle of the FCEV, depending on energy mix of the country, can be over 2.5 times higher than the respective for GV.

The most ecological technology for production of hydrogen is electrolysis for countries using a large part of renewable energy sources in its energy mix. For example, in Norway, FCEV will have 16 times less emissions than GV.

Positive ecological and financial positive effects from replacing the vehicle fleet with FCEV, at the moment and in near future, are not strongly proven.

The results of the present study have to be understood as one indicative simulation, which highlights positive and negative features of FCEV.

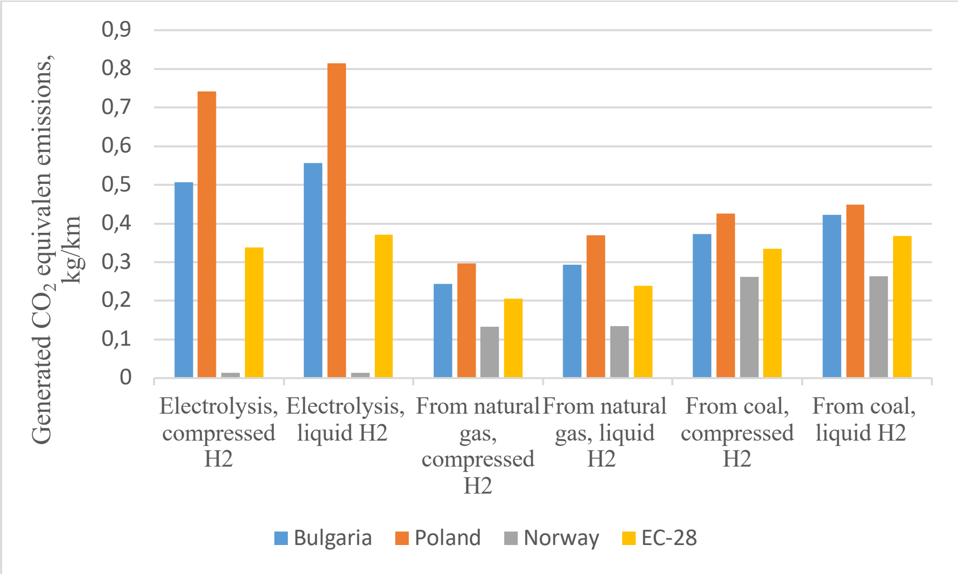

Fig. 10. Generated CO_2 equivalent emissions in *kg/km,* concerning different technologies for production of H_2

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