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POTENTIAL ENVIRONMENTAL LIFE CYCLE IMPACTS OF FUEL CELL ELECTRIC VEHICLES POWERED BY HYDROGEN PRODUCED FROM POLISH COKE OVEN GAS

Summary. This study analysed the greenhouse gas (GHG) emissions of hydrogen fuel cell vehicles'(FCEVs') life cycles. These included models running on hydrogen derived from coke oven gas (COG), which is a by-product of the coking process of coal and includes hydrogen, methane, and other gases. FCEVs and hydrogen have the potential to drive future mobility. Hydrogen can be separated from the COG in the process of pressure swing adsorption to obtain a purity of hydrogen that meets the requirements of a hydrogen FCEV. An environmental life cycle assessment (LCA) of FCEV powered by hydrogen produced from Polish COG was conducted. The direction of hydrogen production strategies in Poland was also presented. The analyses included the entire life cycle of FCEVs with the production of hydrogen from COG in a Polish coke plant. A comparative analysis of FCEVs and other alternative fuels was conducted, and the main determinants of GHG emissions of FCEV were given. Importantly, this is the first attempt at an environmental assessment of FCEVs in Poland.

1. INTRODUCTION

Hydrogen is the future of the automotive industry, both in Poland and worldwide. In a recently published draft strategy to be implemented by 2040, the Polish government estimated that hydrogen cars will not become truly popular until the 2040s or 2050s – that is, in 30 years. The first hydrogen-powered car registered in Poland, the Toyota®Mirai, can cover a range of approximately 550 km on one charge. Other fuel cell models, which are produced by Honda or Hyundai and are available in other countries, can run for more than 700 km without refueling [1]. The main advantage of hydrogen is its heating value, which is three times higher than petroleum and fuel cells. The second major advantage of hydrogen is decreased hazardous tailpipe emissions [2, 3]. Hydrogen is a potential solution for transport as an alternative fuel. Poland is one of the world's major hydrogen producers. Poland is the fifth-largest hydrogen producer worldwide. Hydrogen is mainly used in the petrochemical processes.

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Companies in Poland are very much involved in the development of hydrogen production [4]. Hydrogen for transport is a cornerstone of Poland's hydrogen economy. National companies have wide-ranging interests regarding the development of hydrogen transportation infrastructure, such as refuelling stations for hydrogen-fuelled vehicles. PKN ORLEN S.A focuses on developing hydrogen generation and distribution installations of hydrogen fuel. Several local companies have begun developing hydrogen refuelling stations – for example, the energy companies PKN ORLEN S.A, Polskie Górnictwo Naftowe i Gazownictwo S.A and Grupa LOTOS S.A. There are also plans in Poland to construct a hydrogen-fuelled train. Solaris Bus & Coach S.A. is producing a fleet of hydrogen-fuelled buses in Poland. The uses of hydrogen as a transport fuel and as a technology for energy storage are currently the main areas of growth in Poland, but hydrogen technology remains in the early stages of development [5]. A review of the alternative fuels in Poland was presented previously [6]. Hydrogen is an important element of smart energy solutions. The Polish Hydrogen Strategy contains the main goals of the hydrogen economy development and the directions of activities to achieve them. The scope of the Polish strategy is hydrogen economy development to achieve climate neutrality.

Hydrogen is considered a low-emissions fuel. The only compound released from the exhaust pipe of a vehicle powered by this gas is steam. However, the actual emissions related to hydrogen production depend on how it has been obtained. In Europe and in Poland specifically, the main interest is in the industrial-scale production of hydrogen using renewable fuels. However, to date, hydrogen production in Poland has used coal-based technologies to a considerable extent. Therefore, it is necessary to develop RES-based technology so that the hydrogen obtained is green. Poland accounts for 14% of European hydrogen production. This provides a significant opportunity for Poland to become an important hydrogen producer and to ensure that hydrogen cells intended for drive systems of zero-emission cars are developed in Poland [5]. Fuel cell electric vehicles (FCEVs) do not cause direct exhaust emissions. There is still insufficient infrastructure in Poland.

Numerous initiatives and studies concerning hydrogen production and storage have been undertaken in Poland [6]. Many hydrogen research and demonstration projects are currently underway. Polish scientific and research institutions, as well as industry representatives and oil companies in particular, have been investing hydrogen, with the prospects of climate neutrality and diversification in petrochemical sectors. In 2016 an analysis was carried out on the carbon footprint of the hydrogen production process by the gasification of coal using technologies under Polish conditions [7]. The aim of that study was to analyse the carbon footprint of the production of hydrogen that was perceived as a zero-emission fuel. Another paper [8] presented an analysis of the contemporary low-carbon hydrogen energy market in the territory of Małopolska, which is one of Poland's main administrative regions. An assessment of the motorisation market of FCEVs and battery electric vehicles (BEVs) in Poland was shown in the paper [9].

One hydrogen production method is recovery from COG [10,11]. Carbon dioxide emission in hydrogen production technology from COG was presented in the paper [12]. COG is a by-product of the coking process [13]. A previous work [14] showed hydrogen in a fluidised membrane reactor. COG is one of the by-products of the metallurgical processes [15]. In another paper [16], the steam reforming of coke oven gas to produce high purity hydrogen was demonstrated. COG is one of the sources of hydrogen in Poland.

Hydrogen is an important transport fuel in Poland. Previous research in Poland has focused mainly on the greenhouse gas (GHG) emissions of vehicles, particularly by comparing the LCA for internal combustion engine vehicles (ICEVs) – conventional diesel or gasoline vehicles – with that for electric vehicles (EVs) [17]. The goal of the present paper was to evaluate the GHG emissions for the life cycle of an FCEV powered by hydrogen produced from Polish coke oven gas.

2. MATERIALS AND METHODS

2.1. Goal and scope of analysis

This study aimed to perform a life cycle assessment of FCEV in Poland, considering hydrogen production from COG. The scope of analysis is shown in Fig. 1. The system boundary incorporated the life cycle of FCEVs and hydrogen production. The approach used was ‘from cradle to grave’. The LCA was attributional. The system boundary of the life cycle of FCEV is shown in Fig. 2.

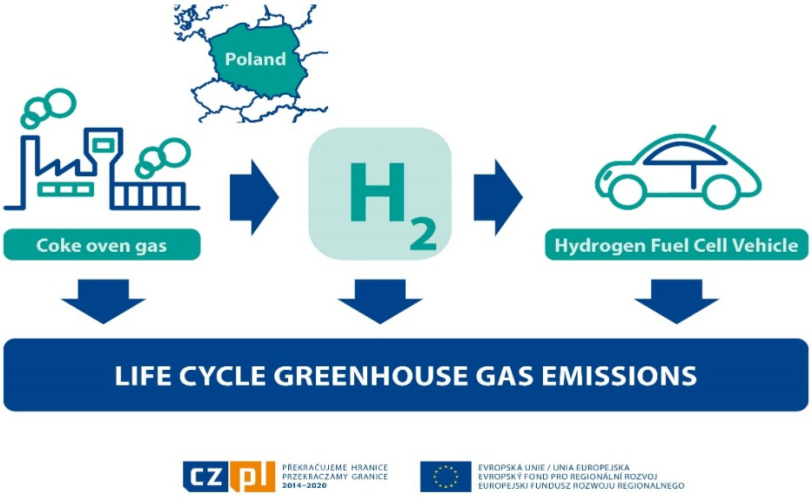

Fig. 1. Scope of analysis of the life cycle GHG emissions of FCEV

LCA analyses of the vehicle concerned the distance travelled by the FCEV, which is why the functional unit (FU) was 1 km. Hydrogen storage and distribution, filling stations, and vehicle decommissioning were ignored. The boundary of analysis included the following major processes for FCEVs powered by hydrogen produced from coke oven gas: hydrogen production, FCEV manufacture and FCEV operation. Coke oven gas contains many impurities, and, therefore, many processes are needed to use the obtained hydrogen for fuel cells that meet the standards of fuel cells. Therefore, the system boundary involves many processes for producing hydrogen from COG (see Fig. 3).

This analysis aimed to predict the potential impact of FCEVs on the GHG emissions in Poland from the hydrogen that was produced from the Jastrzębska Spółka Węglowa (JSW) example, which is a Poland-based coking coal producer. The separation and purification of hydrogen from coal gas were analysed with a pressure swing adsorption system according to JSW technology [18].

2.2. Assumptions, inventories, and LCA method

Hydrogen production from COG used for FCEVs is one of the main scientific research interests related to Poland’s economic prospects. The sources of data used in the study of the life cycles of FCEVs powered by hydrogen produced from Polish coke oven gas are presented in Tab. 1.

To date, LCA analyses conducted in Poland have only addressed coal gasification technology. The potential to use hydrogen for FCEVs and hydrogen production from COG were examined in the present study because companies in Poland are endeavouring to obtain hydrogen intended for transport from coke oven gas. The data used to perform the LCA analysis of hydrogen production were extracted from the experiments and analyses previously conducted in Poland [12] and compiled by means of the Chem CAD® process simulator. Both the detailed data and the electricity consumption information in the process of hydrogen production from COG have been provided previously [10]. Tab. 2 presents the inputs and outputs of hydrogen production from COG.

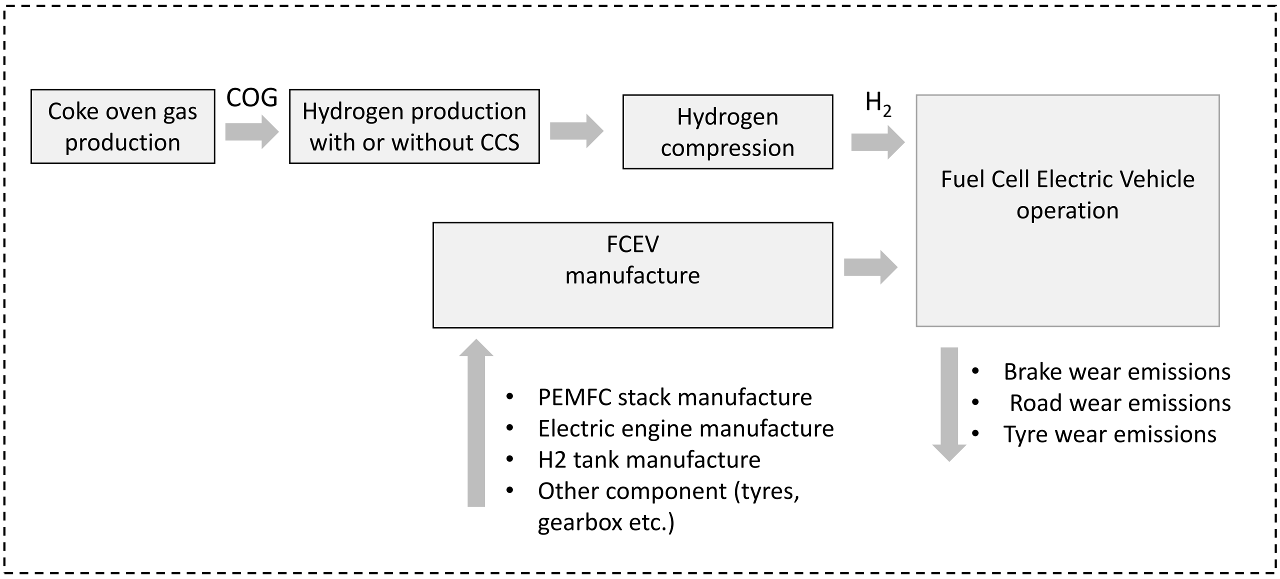

Fig. 2. System boundary of the life cycle of FCEV

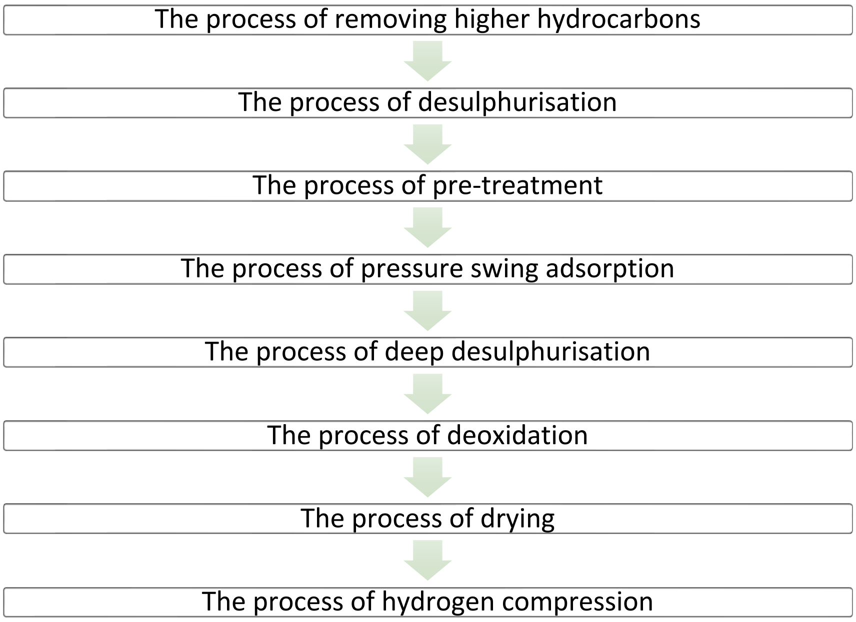

Fig. 3. Necessary processes for obtaining hydrogen from COG

Hydrogen production from COG was analysed using the PSA process [19]. For obtaining hydrogen of the high purity class required for use in FCEVs, COG separation installation should be used. The purity requirements for hydrogen should be in accordance with ISO 14687-2:2012 [30] for a fuel cell with a proton exchange membrane (PEMFC). The consumption of 0.5 kg of hydrogen per day for the FCEV was assumed. Thus, a station with a capacity of 200 kg per day will supply as many as 400 vehicles with hydrogen. Hydrogen from COG (after all processes have been completed) is a clean fuel that can be consumed in FCEV. The efficiency of the energy conversion of FCEVs is very high and is three times higher than in ICEVs. FCEVs do cause environmental harm, and their only emission is water vapour from the tailpipe.

Table 1

The sources of data used in the study

Main phases of LCA	The source of data used in the research
Coke oven gas production	Technological data of COG production [10]
Hydrogen production from COG	TheChem CAD®process simulator [5].
FCEV operation and manufacture	The literature and the Ecoinvent 3 database [24,25]
The carbon footprint of hydrogen produced from coal gasification	National data [7]
GHG emissions of BEVs in Poland	Authors' earlier research [17, 26]

Table 2

Inputs and outputs of hydrogen production from COG [12]

Data inventories	Amount [kg/kg H_2]
Input	
Coke oven gas	4,30
Oxygen	3,24
Tar	1,34
Water supplement	4,03
Steam	3,63
Total	16,54
Output	
Hydrogen	1,00
CO_2	8,34
Acid gas	0,19
Gas for battery	2,79
Waste	4,07
Steam production	0,11
Total	16,54

The specifications for the hydrogen were sourced from Polish companies, and the data for the FCEVs was sourced from the literature and the Ecoinvent 3 database. The LCA GHG emission was used to assess the environmental impact of the studied FCEV. LCA was conducted according to ISO 14044:2006 [31] guidelines. The LCA was done with the SimaPro v.9 package with the Ecoinvent v3 database. According to the ISO standard, the goal and scope of the study were defined, including the system boundary, functional unit, and assumptions.

The second phase involved identifying and analysing the inputs and outputs (LCI – life cycle inventory). The phase of the life cycle impact assessment involved environmental impact analysis according to the chosen methods. The analyses conducted for the GHG emissions analysis included a well to wheel (WTW) analysis, which contained a GHG emissions assessment of the production, transport, and distribution of fuel (in this case, hydrogen), as well as for other phases included within the boundaries of the LCA system. The relevant GHG emissions of FCEVs and hydrogen production from COG were analysed by applying the Intergovernmental Panel on Climate Change method. GHG emissions pose significant problems in the European Union, as well as new challenges according to a

European Green Deal. Aspects of the GHG emissions analysis of vehicles are also fundamental according to the WTW method.

3. RESULTS AND DISCUSSION

An LCA was performed for hydrogen and its application as a fuel in a fuel cell-powered vehicle. Different hydrogen production variants were analysed by considering various sources used for hydrogen production. The alternative fuels were additionally compared with one another. Based on the literature review, specific assumptions were developed, and survey data were collected for a life cycle analysis of hydrogen-powered FCEVs [14, 21, 22, 23]. The LCA results obtained for fuel cell vehicles were presented considering different vehicle components. The findings of the GHG emissions analysis in the life cycle of hydrogen in Poland are presented in Figs. 4 and 5. The GHG emissions associated with energy consumption in the processes of hydrogen production from COG are presented in Fig. 6. The COG routes emit 14.67 CO_2eq without carbon capture and storage (CCS), whereas COG routes emit 6.33 CO_2eq with CCS. Considering that the average CO_2 emissions of Poland's electricity energy in the power grid are very high, the higher electricity consumption in the COG for hydrogen production partly increases GHG emissions. GHG emissions from coal mining and coal transportation are relatively low and, therefore, are irrelevant under national conditions.

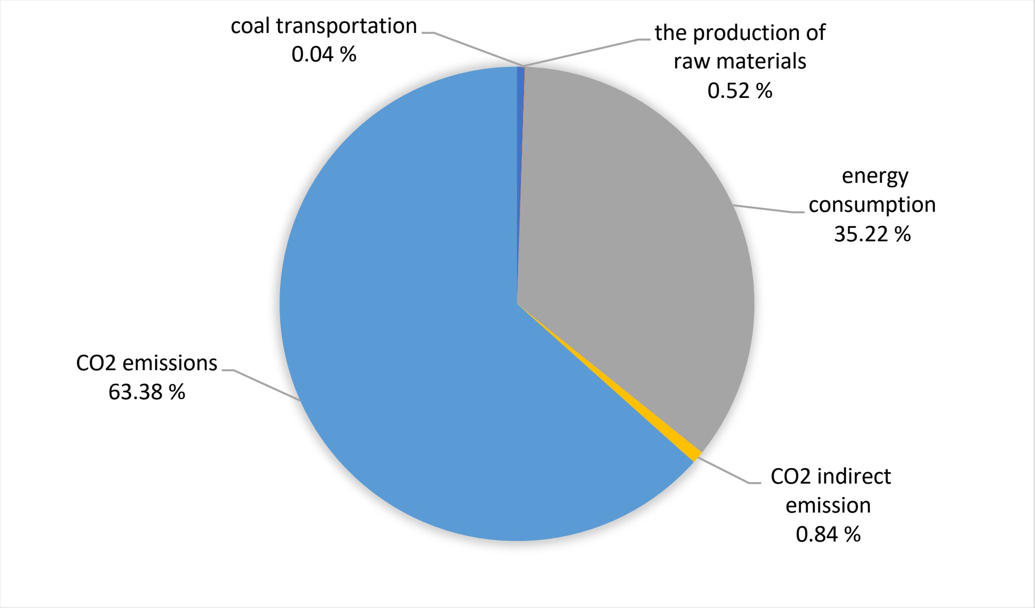

Fig. 4. Shares of GHG emissions in the production of hydrogen from COG without CCS

After the LCA analysis of coke oven gas-based hydrogen production technology, the main sources of GHG emissions were established. These included the following (Fig. 6):

- direct CO_2 emissions (CCS technology) (8.34 kg of CO_2 equivalent per kg of H_2),
- indirect emissions associated with the coke oven gas production process (44.5 g CO_2 eq/MJ of COG), and
- the emissions due to electricity consumption under individual processes (5.33 kg CO_2 eq/kg H_2).

The following results of the GHG emission analyses were obtained from the literature for both the production and operation of FCEVs [24, 25]:

- PEMFC stack – 5 g CO_2 eq/km,
- Vehicle infrastructure (without PEMFC stack) – 40 g CO_2 eq/ km, and
- Vehicle operation (without hydrogen) – 10 g CO_2 eq/km.

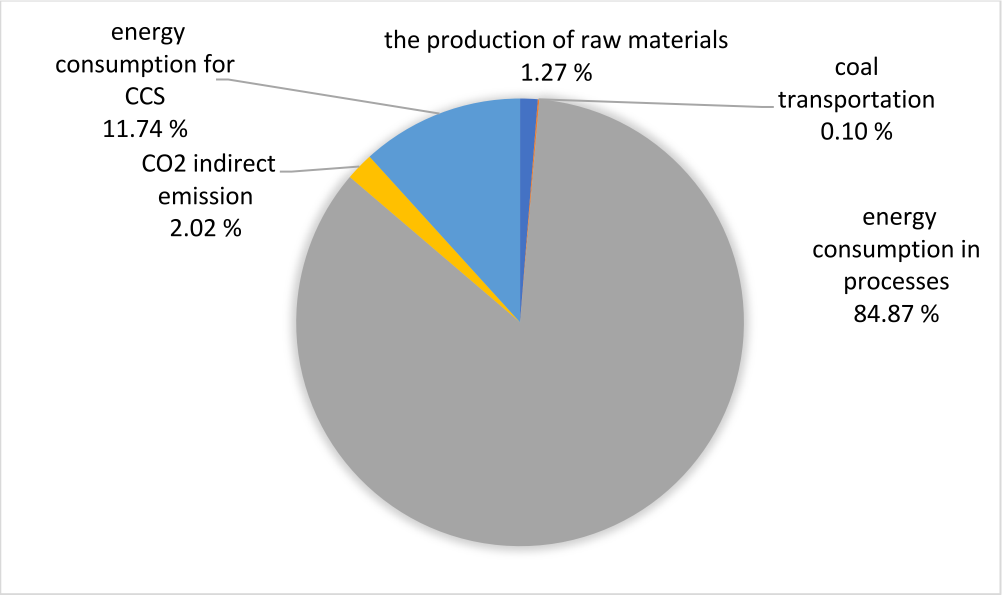

Fig. 5. Shares in GHG emissions in the production of hydrogen from COG with CCS

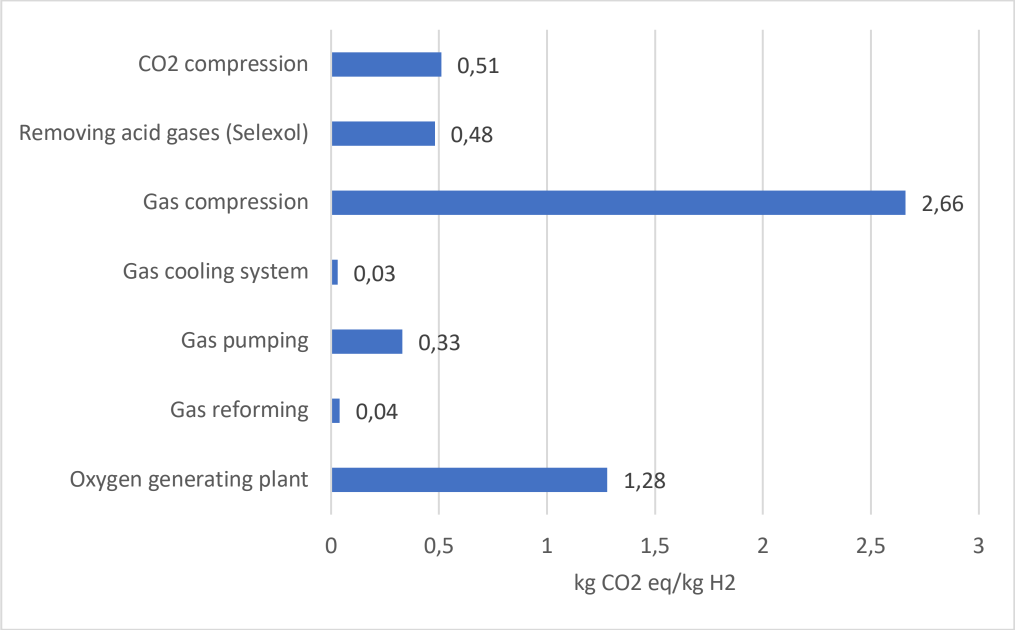

Fig. 6. GHG emissions associated with energy consumption in the processes of hydrogen production from COG

This study analysed the GHG emissions analysis of FCEVs powered by hydrogen produced from coal gasification. Based on national data [7], including the carbon footprint of hydrogen produced from coal gasification and data about FCEVs presented in the literature [24, 25], this study evaluated the GHG emissions of FCEVs. The carbon footprint of the hydrogen production technology based on the gasification of sub-bituminous coal and lignite under domestic conditions was analysed and discussed for the first time in 2016 [7]. The commercial-scale technological solutions available at that time were adopted to calculate the syngas production system parameters. The GHG emissions analysis of hydrogen production by gasification incorporated the processes of coal extraction, mechanical treatment, transport of coal to the gasification plant, the gasification itself, CO_2 capture, and carbon storage. The results of the GHG emissions analysis of hydrogen production from coal gasification with CCS and without CCS in Polish conditions were presented [7]. The authors in [7] presented the results of LCA analyses for 1 kg of hydrogen and a functional unit of 1 kg H_2. This study extended the system boundary to the FCEV and applied the obtained hydrogen to the FCEV. In this study, the functional unit was 1 km, and the system boundary was extended.

In this study, a comparative analysis was performed to compare the effect of FCEVs powered by hydrogen produced from COG on GHG emissions and the effect of FCEVs powered by hydrogen produced from coal gasification on GHG emissions. In addition, the results of the present analyses were compared with those obtained by other authors. These results were compared against an FCEV life cycle assuming such diverse sources of hydrogen as natural gas, biomass, and electrolysis (Table 3).

The analysis of the GHG emissions of FCEVs revealed that GHG emissions of hydrogen production from COG were lower than for hydrogen production from coal gasification. Furthermore, FCEVs powered by hydrogen obtained from coal gasification (without CCS technology) were characterised by the highest GHG emissions indicator, while the biomass gasification technology utilised for hydrogen production showed the lowest GHG emissions indicator – therefore, this is the best hydrogen production alternative.

In earlier studies by the authors of the present work, GHG emissions were evaluated for BEVs whose batteries were charged with electricity supplied from the power grid, namely, the Polish electric energy mix [17, 26]. According to the authors' earlier research [17, 26], electricity is the main source of GHG emissions for BEVs. In the case of BEVs in Poland, the GHG emissions were 41.4 kg CO_2eq/150,000 km (in 2015). By 2050, these emissions are expected to decrease to 25.8 kg CO_2eq/150,000 km. From 2015–2050, the GHG emissions attributable to BEVs range between 172 and 276 gCO_2eq/km, depending on the electricity source, for the years 2015-2050.

Table 3

Comparative analysis of the results of original studies

Hydrogen production system	GHG emissions from FCEV life cycle [g CO_2 eq/km]	Sources
Hydrogen from coke oven gas without CCS	156	This study
Hydrogen from coke oven gas with CCS	97	This study
Hydrogen from coal gasification without CCS	215	This study according to [7]
Hydrogen from coal gasification with CCS	121	This study according to [7]
Hydrogen from steam methane reforming	140	[25]
Hydrogen from biomass gasification	60	[25]
Hydrogen from electrolysis – wind power	70	[24]

The present study indicates that the GHG emissions from FCEVs range between 60 and 215 g CO_2eq/km, meaning that the use of hydrogen, even if produced using fossil fuels, is a better solution for transport than electric vehicles. The exception is hydrogen from coal gasification without CCS technology.

FCEVs do not generate local emissions of compounds such as NO_X, nor do they emit any CO_2. At the tank-to-wheel (TTW) stage, only FCEVs and BEVs are completely carbon-neutral, whereas other decarbonisation options – such as vehicles powered by biofuels, natural gas, and hybrids – are not. Compared to diesel and petrol ICEVs, emissions should be considered in the same way as emissions from fuel production at the TTW stage and well-to-tank (WTT) stage. The WTT emissions for ICEVs include emissions from petroleum extraction, transport, refining and processing, and distribution to service stations. Regarding BEVs, the WTT emissions depend on the electricity mix of the country where the vehicle is usually charged. An advantage of FCEVs over BEVs is that fuel cells are less energy-intensive than batteries. The environmental impact of FCEVs at the WTT stage depends on how the hydrogen is produced.

This study analysed the carbon footprint of the hydrogen supply chains for fuel cell vehicles. Notably, not only do FCEVs reduce GHG emissions when compared to petrol-powered vehicles, but these vehicles release almost no emissions during their operation, which can improve air quality, particularly in urban areas. The findings obtained here corroborate those reported by others who have conducted LCA analyses of fuel cell vehicles [27,28]. In those studies, different sources of electricity used for electrolysis were considered, which made it possible to demonstrate that the hydrogen production option based on electrolysis entails high environmental indicators when the electricity used for electrolysis is produced from fossil fuels. In contrast, when electricity is produced by hydropower or wind power, electrolysis, as a hydrogen production variant, has the lowest environmental impact throughout the hydrogen life cycle.

Fossil fuels consumed to produce hydrogen (i.e. hydrogen pathways based on natural gas, coal, and grid power), which are intended to be the fuel of the future, cannot be regarded as a green alternative. Only fuel cell vehicles powered by hydrogen produced by RES-based techniques – in particular, wind and hydropower – can reduce GHG emissions. LCA is a useful tool for assessing the environmental impact of fuel cell vehicles using different fuels. A well-to-wheel hydrogen life cycle analysis demonstrated that hydrogen is a promising solution for reducing GHG emissions. However, concerning hydrogen fuel cell vehicles, this solution can cause even higher GHG emissions than those attributable to internal combustion engine vehicles if the hydrogen is produced using fossil fuels. Hydrogen-powered vehicles represent one of the three main options for low-carbon transport, along with vehicles that run on biofuels and electric vehicles. Unlike biofuels, hydrogen imposes no impact on land use or air quality; also, hydrogen offers larger running ranges and shorter charging times than BEVs. However, electric cars are more advanced than hydrogen-powered cars because of their lower costs and easily accessible infrastructure [29].

4. CONCLUSIONS

This analysis has demonstrated that coke oven gas includes hydrogen and that hydrogen can be separated from coke oven gas through the process of PSA to obtain a product with a purity of 99.999%, which is the level required for the purity of hydrogen fuel cells. In this study, fuel cells were used as mobile generators to power vehicles. It has been shown that GHG emissions from the COG process are low and that hydrogen production from COG in Poland has the potential to become a future source of green energy. The obtained results showed that the GHG emissions from FCEVs powered by hydrogen from COG with CCS (97 g CO_2 eq/km) are lower than the GHG emissions from FCEVs powered by hydrogen produced from steam methane reforming (140 g CO_2 eq/km) and coal gasification (215 g CO_2 eq/km without CCS and 121 g CO_2 eq/km with CCS). It has also been shown that hydrogen production from biomass gasification has the lowest GHG emissions indicator, meaning it is the best alternative for hydrogen production.

Currently, the biggest problem in Poland is no longer the fuel cell technology itself but the lack of infrastructure to distribute the hydrogen fuel. The very low availability of hydrogen refuelling stations, as well as the special conditions required to install hydrogen tanks in vehicles, determine the use of this energy source in delivery vehicles and trucks. Hydrogen is a promising decarbonisation option for heavy goods vehicles, buses, ships, trains, large cars, and commercial vehicles in Poland. The analyses performed in the present study showed that coke oven gas is a potential in the production of hydrogen for transport applications in Poland.

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