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ENVIRONMENTAL FOOTPRINTS OF CURRENT AND FUTURE ELECTRIC BATTERY CHARGING AND ELECTRIC VEHICLES IN POLAND

Summary. This paper presents the results of environmental footprints of the life cycle of electric passenger cars, with a current and future electric battery charging analysis in Poland. The shares of the sources of electricity generation in the energy systems of Poland in the years 2015–2050 were used to perform the chosen environmental footprints of current and future electric car battery charging. This article discusses the water and carbon footprints of electric passenger cars in Poland. The carbon footprint was determined using the Intergovernmental Panel on Climate Change (IPCC) method. The water footprint was calculated using the Hoekstra method. The environmental footprints were provided by the SimaPro 8 package with the Ecoinvent 3 database. The obtained results showed that the carbon footprint and water footprints of electric passenger cars in Poland are primarily related to the type of electricity used to charge electric car batteries. The results showed that current and future carbon footprint indicators of electric cars in Poland are lower than those for petrol cars, but the water footprint indicators of electric cars are higher than those for petrol cars. In the case of petrol cars, the main determinant of the carbon footprint is direct emission during the exploitation stage and the main determinant of the water footprint is car production.

1. INTRODUCTION

Road transport is one of the main sources of impact contributing to the pollution of cities. Water demand and greenhouse gas emissions (GHG) from transport have increased over the last few years. Transport is a significant source of particulate matter, nitrogen dioxide and noise in Europe [1]. Sustainable transport provides a balance between social and economic factors, and spatial development and environmental protection. The transport sector has the potential for reduction of environmental emissions and sustainable urban development [2]. As electric vehicles are becoming an important element in the development strategy of the automotive industry in Poland, this analysis contributes toward assessing the carbon and water footprints of electric passenger cars. Emissions from the transport sector are not reducing enough to limit its environmental and climate impacts in Europe. According to the European Environment Agency, greenhouse gas emissions from transport have been increasing since 2014. In 2016, the transport sector contributed 27% of total EU-28 greenhouse gas emissions [3].

The transport sector has the greatest environmental footprint of all industries. Environmental footprints are quantitative measurements describing the use of natural resources by humans. With negative environmental impacts, there is an increased interest in measuring and reducing environmental burdens. New methods to measure environmental impacts like environmental footprints, life cycle assessment, life cycle sustainability assessment and eco-efficiency are being developed. Among the metrics that allow measurements of environmental sustainability, environmental footprints play a significant role in the sustainability assessment [4]. Apart from the energy sector, the transport sector has been the primary source of GHG emissions in the European Union countries since 1990. Approximately three-quarters of the emission from this economic activity are generated by road transport, in particular, passenger cars. According to the European Environment Agency, electric vehicles (EVs) are anticipated to be a key component of Europe's mobility system, helping reduce impacts on climate change and air quality. The largest potential reduction in greenhouse gas emissions occurs during the use of the electric vehicles. The use of electric vehicles instead of gasoline vehicles can save (about 60% of) greenhouse gases in all or in most of the European Union Member States, depending on the estimated consumption of the vehicles [5]. Compared with diesel, electric vehicles show average GHG emission savings of around 50% and no savings at all in some countries of European Union. The electric vehicles sector is developing worldwide. This development is accompanied by extensive research and environmental analysis of electric vehicles [3, 6]. According to the Transport and Environment Reporting Mechanism, electric vehicles offer important opportunities to reduce GHG emissions and local air pollution [7]. According to the newest Information and Forschung (IFO) research, electric vehicles will barely help cut CO_2 emissions in Germany over the coming years [8]. Almost all European Union countries generate significant CO_2 emissions from charging the vehicles' batteries using their national electricity mix. Natural gas combustion engines are represent a better technology for transitioning to vehicles powered by hydrogen or "green" methane in the long term. Hydrogen-powered electric vehicles or vehicles with combustion engines powered by green methane offer great potential. The first attempt at a comparative life cycle assessment of electric vehicles in Poland and the Czech Republic that includes analyses of the life cycle assessment for present and future electricity generation systems for charging electric vehicle batteries was presented in the paper [3]. Electricity generation in Poland is dominated by solids. Hard coal constitutes more than 60% of the coal used for energy production; the remaining part is lignite. Poland has the highest share of coal in electricity generation among all the International Energy Agency (IEA) countries. Despite the rapid growth of renewable sources, Poland is still among the IEA member countries with the lowest shares of renewable energy sources. Coal will continue to be the main source of energy for years to come. No nuclear power is currently produced in Poland; nuclear energy is planned after 2035. Despite reducing the share of solid fuels in electricity generation in Poland, their share has the greatest impact on the environment. The environmental assessment of electricity sources in Poland showed that the environmental impact is determined by the consumption of solids, including both hard coal and lignite [9]. In Poland, government actions as well as a regulatory package are aimed at increasing the use of alternative fuels and supporting the development of electromobility. On 28 December 2017, the Electromobility Law was adopted by the Polish Government. The Act of 11 January 2018 on Electromobility and Alternative Fuels came into force on 22 February 2018. It establishes a system of incentives for the promotion of the use of vehicles powered by alternative fuels, mainly electricity, and also introduces mechanisms for initiating investments in the necessary infrastructure. The Act introduces into Polish law the requirements of Directive 2014/94/EU of 22 October 2014 on the deployment of infrastructure for the use of alternative fuels.

The purpose of this work was to evaluate the potential environmental impacts, including environmental footprints, of battery electric passenger cars, taking into account the current and future energy used to charge batteries in Poland from 2015 to 2050. For this purpose, the authors used two new methods of life-cycle impact assessment like the carbon footprint method for life-cycle greenhouse gas emission assessment and the water footprint method for cumulative water demand assessment.

2. MATERIALS AND METHODS

The aim of this paper was to evaluate the chosen environmental footprints of electric passenger cars' life cycles (including passenger car production, battery production, road construction, car use, maintenance and disposal) and battery charging, taking into account the trends in electricity supply to charge batteries from 2015 to 2050. The environmental footprint indicators were obtained based on the life-cycle assessment (LCA) technique, which allows identification of environmental aspects related to the life cycle of vehicles, both directly and indirectly. Carbon footprint indicators were obtained using the Intergovernmental Panel on Climate Change (IPCC) 2013 method. IPCC 2013 is the successor of the IPCC 2007 method, which was developed by the Intergovernmental Panel on Climate Change. It contains the climate change factors of IPCC with a timeframe of 100 years. The total amount of carbon footprint has direct and indirect impacts on human activities expressed by a reference unit of kg CO_2. The carbon footprint is calculated based on the global warming potential (GWP).

Water management already plays a major role in the electricity and transport sectors [10]. The water footprint indicators were obtained using the method developed by Hoekstra [11]. The water footprint was calculated with SimaPro (Pré Sustainability, Amersfoort, The Netherlands), which allows for the identification of regions with high water stress. A water footprint is a measure of how much water a product uses and which direct and indirect environmental impacts result from this. This method enables the understanding and management of water use in the life cycle of a product. Water footprint is a significant determinant of electromobility development, but, so far, the research presented in the literature on environmental impact assessment has been scarce. The water footprint methodology is a new concept introduced to quantify cumulative direct and indirect water use along the supply chains in water resource management. In this paper, the amount of water used for electric vehicle battery charging included direct and indirect water usage. Direct water use is physically used water during the process, while indirect use is water needed to create something used in the process. This indicator is applied to the consumed water volume and only assesses used water. The total amount of water footprint is expressed by a reference unit of m^3. The environmental footprint evaluation was performed with the life cycle assessment (LCA) technique. The LCA was conducted in accordance with ISO 14044:2006 [12]. The goal and scope of the study, functional unit, system boundary and basic assumptions were defined. The results of the environmental footprints were calculated and the main sources of environmental indicators were identified. Environmental footprint assessment was performed using the SimaPro v.8 package with the Ecoinvent v.3 database [13]. The basic assumptions used for the vehicle life cycle are from the databases [14]. Detailed inventory data and assumptions were presented in the paper [3]. In a comparative analysis, the functional unit should be the same for all the compared systems. The functional unit (FU) of this study was 100 km. The system boundary includes the passenger car life cycle: passenger car production, battery production, electricity supply for EVs, road construction, car use, maintenance and disposal of the components. In the use phase of EVs, electricity consumption was tracked throughout its power supply chain. The boundary system covered the electricity mix in Poland from 2015 to 2050.

A car equipped with a lithium-ion battery was chosen for the analysis because it is the most frequently used battery for EVs. The inventory data included battery production with a dataset for the lithium-ion type battery [15]. The electricity mix used for battery charging is one of the most important parameters for the data, and it is crucial to understand which type of electricity mix will be used to charge the vehicle battery. The analyses were carried out on the energy used for battery charging from the current electricity grid and on the future electricity grid for the years 2015–2050. Data pertaining to the energy systems used to charge electric car batteries in Poland were developed on the basis of national data [16].

3. RESULTS

Based on the performed analysis, the determinants of the chosen environmental footprints of electric passenger cars were established. The results of the assessment of the carbon and water footprints of electric passenger cars in Poland in 2015 are presented in Fig. 1 and Fig. 2, respectively.

3.1. Carbon footprint of electric passenger cars

Based on an analysis, it was found that the main determinant of carbon footprint for the cars in Poland is the electricity used to charge vehicle batteries (Fig. 1). Electricity to charge batteries constituted 72,93% of the footprint for electric cars in Poland in 2015. A large proportion of the carbon footprint is also related to the production of passenger cars (17,04%). The main determinant of the water footprint for electric passenger cars is related to the electricity used to charge the vehicle batteries, which constituted 72,23% in 2015 (Fig. 2).

We performed in-depth analyses of the water and carbon footprints of the electricity sources from Poland's electrical power generation system used to charge vehicle batteries. Analysis was performed in the program SimaPro. The results of the analysis are shown in Tables 1 and 2.

Table 1

Share of water footprint of electricity sources used to charge vehicle batteries in Poland

Unit	Hard coal	Lignite	Oil	Gas	Biomass	Hydro	Wind	Solar	Total
m^3/FU	7,985	2,025	0,002	0,042	0,012	0,001	0,011	0,000	10,078
%	79,230	20,096	0,018	0,421	0,116	0,008	0,110	0,002	100,000

Table 2

Share of carbon footprint of electricity sources used to charge vehicle batteries in Poland

Unit	Hard coal	Lignite	Oil	Gas	Biomass	Hydro	Wind	Solar	Total
kg CO_2eq/FU	604,029	394,027	0,088	13,591	2,840	0,061	0,940	0,015	1015,592
%	59,476	38,798	0,009	1,338	0,280	0,006	0,093	0,002	100

The use of hard coal and lignite for energy systems in Poland accounts for 99.3% of the water footprint, including hard coal, 79.23%, and lignite, 20.10%. Other energy sources (including oil, gas, biomass, hydro, wind and solar) constitute a 0.67% share of the water footprint in the energy system (Table1). The use of hard coal and lignite for the energy system in Poland accounts for 98.28% of the carbon footprint, including hard coal, 59.48 %, and lignite, 38.80%. Other energy sources (including oil, gas, biomass, hydro, wind and solar) constitute a 1,72% share of the carbon footprint in the energy system (Table 2).

The analysis of the electricity sources used to charge vehicle batteries showed that the main determinant of the negative impact on the environment of energy systems in Poland was the consumption of solid fuels, both hard coal and lignite.

Comparative analyses of environmental carbon footprints of current and future electric passenger cars were performed considering the changes in the sources of electricity generation in Poland (Fig. 3 and Fig. 4). Factors other than electricity, such as passenger car production, battery production, maintenance and road wear, remained constant over the time frame of the study. The obtained results showed that the carbon footprint was 27.46 kg CO_2eq/FU in 2015, and will be 16.50 kg CO_2eq/FU in 2050. The value of the carbon footprint from 2015 over the next 35 years will decrease (Fig. 3). Based on the electricity generation analysis by source (in the years 2015–2050), the shares of each source of electricity supply for environmental footprints were evaluated. In Fig. 4, the carbon footprint from each energy source for battery charging in Poland is presented.

We performed an analysis of the influence of renewable energy sources (RES), like biomass, hydro, wind and solar energy, on water and carbon footprints. In the case of analysis of the water footprint, the share of RES constitutes 0.24%, while in the case of carbon footprint analysis, the share of RES constitutes 0.38%; therefore, their shares were considered as negligible.

The influence of renewable energy sources (RES), like biomass, hydro, wind and solar energy, on the environmental footprints is insignificant; therefore, they are presented together in Fig. 4 and Fig. 6.

Comparative analyses showed that the carbon footprint indicators of electricity generation in Poland used to charge vehicle batteries will have decreased by 2050. Based on the carbon footprint analysis of electricity sources, we found that hard coal used in power plants in Poland is the main source of the carbon footprint of electric vehicle battery charging (Table 2).

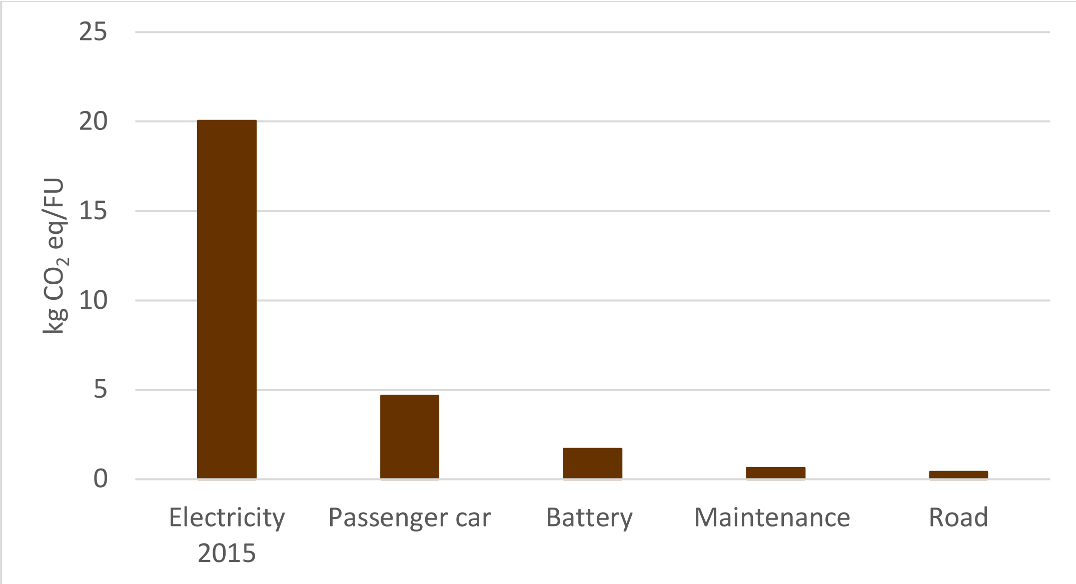

Fig. 1. Main sources of carbon footprint of electric passenger cars in Poland in 2015

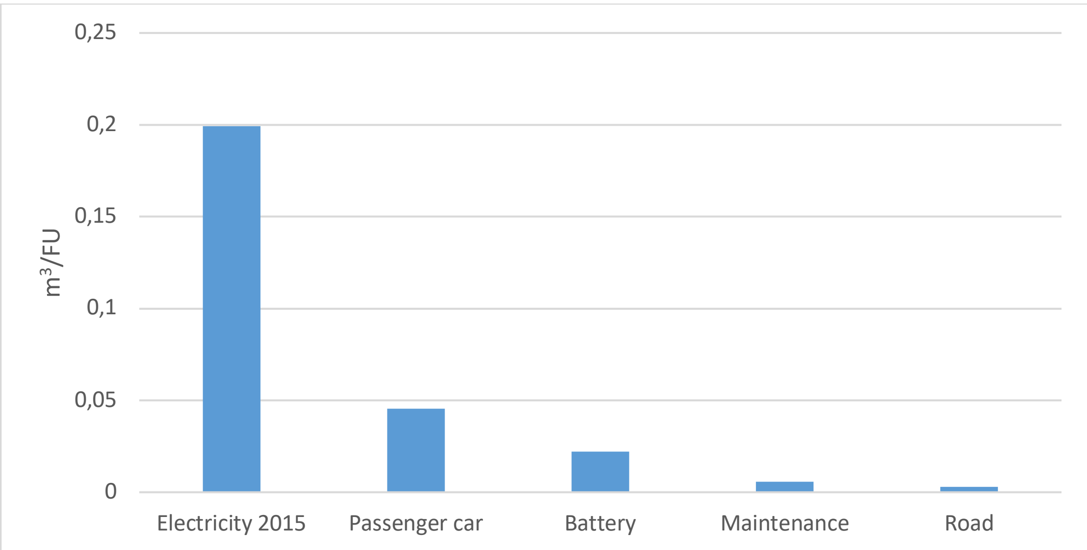

Fig. 2. Main sources of water footprint of electric passenger cars in Poland in 2015

3.2. Water footprint of electric passenger cars

Comparative analyses of environmental water footprints of current and future electric passenger cars were performed considering the changes in the sources of electricity generation in Poland (Fig. 5 and Fig. 6). Factors other than electricity, such as passenger car production, battery production, maintenance and road wear, remained constant over the time frame of the study.

The water footprint of electric cars was 0.27 m^3/FU in 2015; in 2050, the potential impact on water footprint will be 0.17 m^3/FU. The value of the water footprint from 2015 over the next 35 years will decrease too (Fig. 5). Fig. 6 shows the water footprint from individual energy sources for electric battery charging in Poland. Water footprint indicators of electricity generation used to charge batteries will have decreased by 2050. This shows that the main source of the negative impact associated with the water footprint is the electricity from hard coal and nuclear power. A large contribution to the water footprint of electricity from the energy sources is associated with the operational phase, where water is lost through cooling processes using freshwater. According to [17], electric power generation is dependent on water resource availability for cooling. According to [18], increases in dry cooling and reclaimed water can reduce freshwater use for cooling.

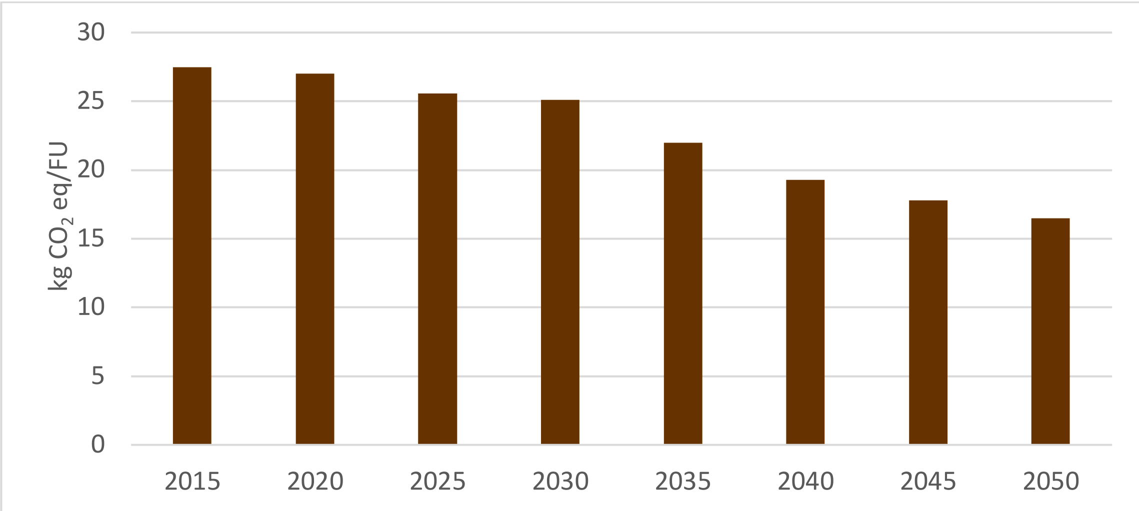

Fig. 3. Carbon footprint for current and future electric passenger cars in Poland

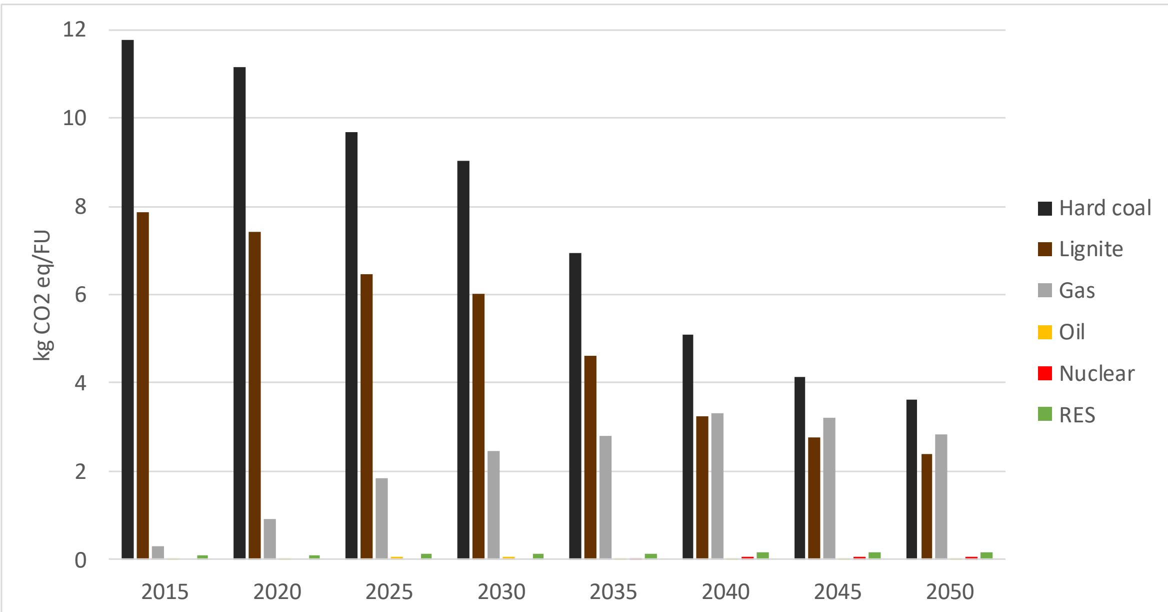

Fig. 4. Carbon footprint of battery charging of electric cars in Poland

The value of the environmental footprints of electrics passenger cars from 2015 over the next 35 years will decrease. The performed analysis showed that this was primarily affected by the decreased share of solids (hard coal and lignite) in the energy sources used for electricity. The performed analysis showed that environmental footprints (including carbon footprint and water footprint) were primarily affected by changes in the sources of electricity generation in Poland, especially the decreased share of solids in electricity generation. Electricity for battery charging is the main determinant of the analyzed environmental footprints for the current and future electric passenger cars in Poland. A decrease in the values of the footprint indicators is caused by the reductions in the share of solids (hard coal and lignite) as the source of electricity generation.

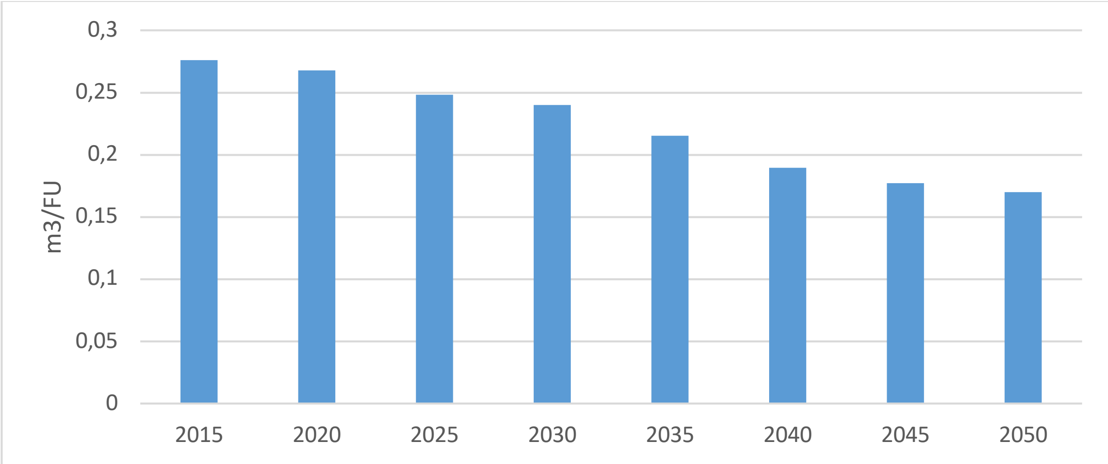

Fig. 5. Water footprint for current and future electric passenger cars in Poland

In addition, a comparative analysis of environmental footprints of electric passenger cars and petrol-fueled cars was performed. In Poland, in recent years, more than 55% of the cars were petrol fueled. The specification and life-cycle inventory for the petrol car were based on the Ecoinvent database and a previous study [3]. The results of the comparative analysis of the carbon and water footprints of petrol-fueled and electric passenger cars are presented in Fig. 7 and Fig. 8.

It was found that current and future carbon footprint indicators of electric cars in Poland are lower than those for petrol cars (Fig. 7). In the case of petrol cars, direct greenhouse gas emission during the exploitation stage (representing 59%) is the main determinant of the carbon footprint, while in the case of electric cars, the production of electricity is the main determinant (representing, respectively, 72% in 2015 and 55% in 2050).

The obtained results showed that in Poland, the water footprint indicators of electric cars are higher than those for petrol cars (Fig. 8). In the case of petrol cars, the main determinant of the water footprint is car production (representing 65%), while in the case of electric cars, the main determinant is the production of electricity (representing, respectively, 64% in 2015 and 45% in 2050).

4. CONCLUSIONS

It was found that the main determinant of carbon and water footprint for electrics cars in Poland is the electricity used to charge vehicles. Comparative analyses of environmental footprints of current and future electric passenger cars were performed considering the changes in the sources of electricity generation in Poland. In the future, an increase in the generation of electricity from alternative sources and nuclear from 2035and a decrease in electricity generated from solids are expected, which will affect the results.

The performed analysis showed that the carbon and water footprints were primarily affected by changes in the sources of electricity generation in Poland, especially the decreased share of solids in electricity generation. A decrease in the values of the footprint indicators is caused by reduction in the share of solid fuels (hard coal and lignite) as the source of electricity generation. It was shown that electric cars are not zero emission throughout the life cycle; components like electricity generation for battery charging, manufacturing of the vehicle and production of battery need to be considered.

The obtained results showed that current and future carbon footprint indicators of electric cars in Poland are lower than those for petrol cars, but the water footprint indicators of electric cars in Poland are higher than those for petrol cars. In the case of petrol cars, the main determinant of the carbon footprint is direct emission during the exploitation stage and the main determinant of the water footprint is car production.

The results of this study may be useful as the first step toward a holistic approach to a vehicle life cycle. The environmental footprint analyses of electric passenger cars carried out so far will be used for eco-efficiency and sustainability assessments of e-mobility.

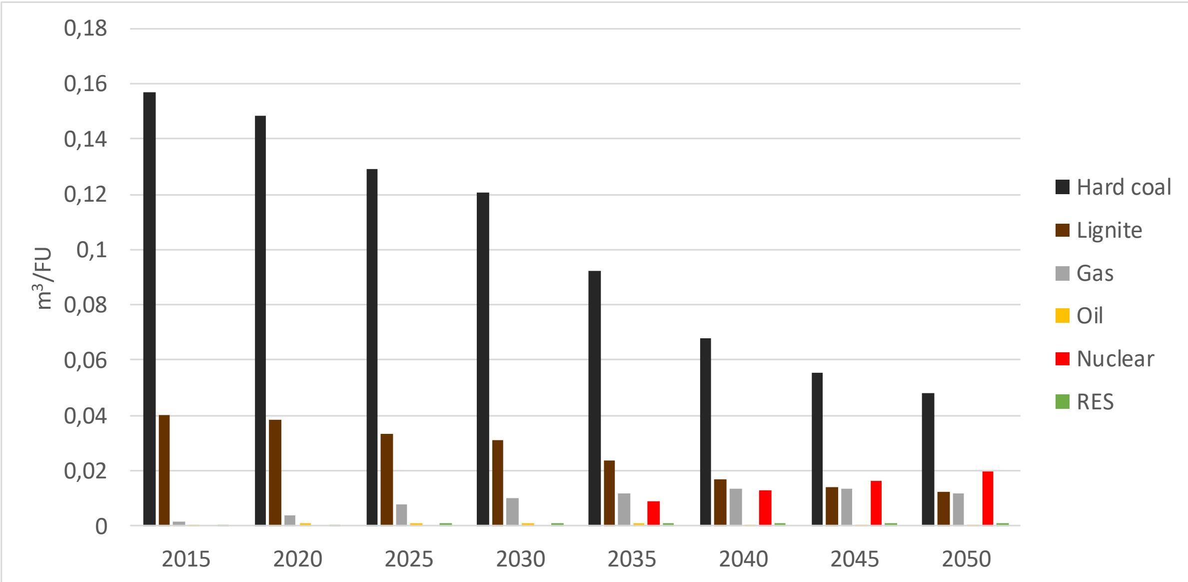

Fig. 6. Water footprint of battery charging of electric cars in Poland

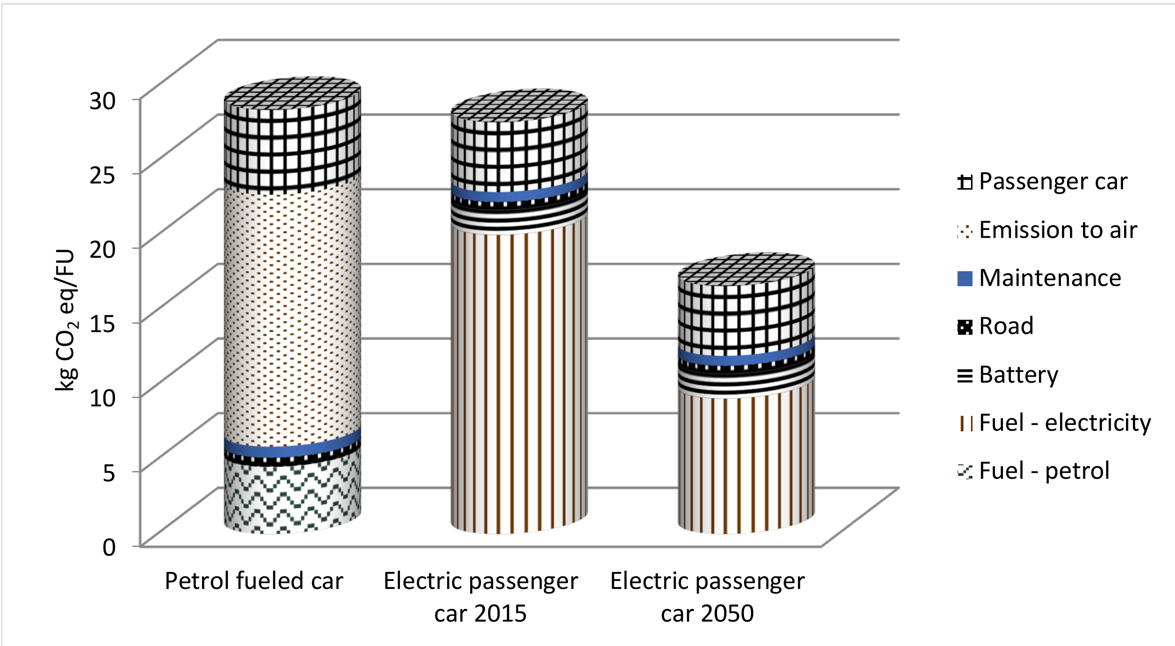

Fig. 7. A comparative analysis of the carbon footprint of petrol-fueled and electric passenger cars

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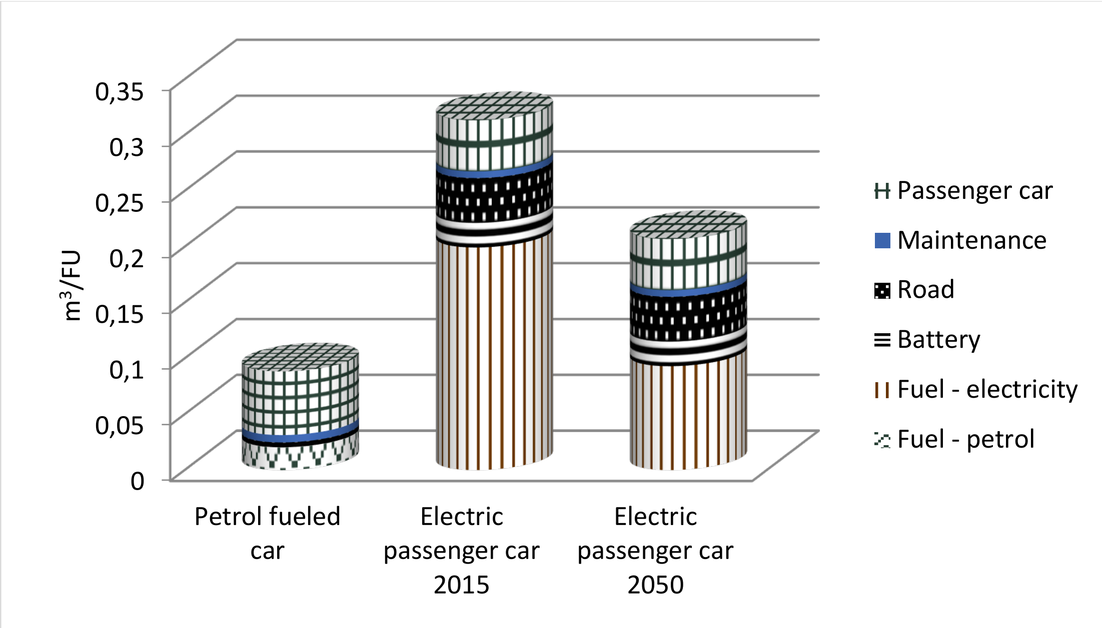

Fig. 8. A comparative analysis of the water footprint of petrol-fueled and electric passenger cars

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