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Comparison of pollutant emissions from various types of vehicles

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This article compares the equivalent emissions from battery electric vehicles (BEVs) with those of internal combustion engines vehicles (ICEVs) and hybrid vehicles (HV). The considerations focused on the dependence of the equivalent emission from electric cars on the official/national Polish energy mix (which is still mainly based on hard coal). The results of mathematical simulations of the impact of the fuel type on pollutants' emissions are presented. The article also focuses on the effects of the fuel used in internal combustion engines vehicles (LPG, CNG, petrol, diesel, hydrogen) and the official/national Polish energy mix for battery electric vehicles on carbon dioxide (CO_2), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and sulphur dioxide (SO_2) emissions.

Key words: *ICEV, BEV, emission, energy mix, air pollution*

1. Introduction

The negative impacts of air pollution on public health and the environment have been a cause of global concern. The Paris Climate Agreement of 2015 [20] outlined a goal to achieve carbon neutrality by 2050 and a target for carbon reduction by 2030, with each country taking up a role in achieving this. The transportation sector is a significant contributor to air pollution, with fossil fuels in internal combustion engines producing carbon dioxide (CO_2).

Road transport is responsible for around one-fifth of the EU's total greenhouse gas emissions, with emissions showing an increasing trend. The case for moving towards zero-emission mobility [4, 17] becomes even more substantial and more apparent in the context of the drive to reduce energy dependence as soon as possible in the EU, given that road transport also accounts for one-third of the EU's total final energy consumption.

The European Green Deal [20] stipulates the goal of attaining climate neutrality by 2050 and an ambitious interim target of reducing net greenhouse gases (GHGs) emissions by at least 55% by 2030 relative to 1990 levels. This is in line with the EU's dedication to global climate action as per the Paris Agreement [17, 20].

The European Green Deal and the goal of achieving climate neutrality are having an impact on the progress of battery electric vehicles (BEVs) [5, 17, 20].

Electric vehicles are often seen as an environmentally-friendly form of transportation, but the emissions produced by them are dependent on the types of fuels used to produce electricity in the country where they are being used. It can refer to vehicles powered mainly from renewable energy sources as being "100% ecological" or "climate-friendly" [18].

According to the latest submission of the national inventory of air pollutant emissions [1, 14, 15], most of the public power in Poland is generated using solid fuels – that's 81% of the total energy mix. Mainly, this means using of hard coal and lignite. The energy sources used in Poland affect the air pollutants generated by electric vehicles, resulting in a transfer of carbon emissions from other sectors into the road transport sector. The effects that electric vehicles have on the environment are largely determined by the energy sources used in the countries where they are produced.

Electric vehicles in Poland can be seen as a source of carbon emissions that have been transferred from the public power and energy sector to the transportation sector. This implies that the environmental impact of electric vehicles is largely dependent on the type of energy that is used to produce electricity in the country. The study [8] shows that the amount of air pollutants created by battery electric vehicles (BEVs) and internal combustion engines vehicles (ICEVs) can be compared based on the energy sources used to produce electricity. This gives researchers a chance to examine the environmental impacts that may come about because of battery electric vehicles and the utilization of energy generated from non-renewable sources [8].

The importance of battery electric vehicles in meeting environmental objectives cannot be overstated, however the extent of their environmental advantages varies based on a variety of factors such as the energy source, the type of air pollutants and greenhouse gases present, and the specific kind of electric vehicle. Undoubtedly, the advantage of battery electric vehicles is shifting the source of transport-related air pollution from roads to power plants [7]. The potential of electric vehicles to cut back on-air pollutants and greenhouse gases may not be fully realized if the electricity used to power them is sourced from non-renewable sources such as coal and oil [18]. In China, research carried out by Huo et al. [6] indicates that electric vehicles can lead to a three to tenfold increase in SO_2 emissions and a doubling of NO_x emissions when compared to internal combustion engine vehicles (ICEVs) [18], given that the majority of electricity is generated from coal.

Electric vehicles do not have the capability to completely reduce all air pollutants and greenhouse gas emissions. Huo et al. [6] demonstrated that battery electric vehicles technology has the potential to reduce greenhouse gas emissions by 20%. However, it may also augment the concentrations of particulate matter (PM both PM10 and

PM2.5), nitrogen oxides (NO_x) and sulphur dioxide (SO_2). According to Nichols et al. [15], battery electric vehicles are capable of decreasing emissions of greenhouse gases, NO_x, and PM10, yet produce substantially higher SO_2 emissions than cars with an internal combustion engine. There is proof that the particulate matter generated beyond exhaust systems varies between battery electric vehicles and internal combustion engine vehicles, as the mass of the vehicle can affect non-exhaust emissions [19, 20]. The amount of wear and tear on tires, brakes, and roads increases significantly for heavy vehicles (50% more than on medium and small cars, which weigh 1600 kg and 1200 kg, respectively) [19]. On average, electric vehicles are about 24% heavier than cars with combustion engines [21, 22].

In addition to energy generation and consumption, the type of electric vehicle is also an essential factor in the environmental benefits of electric mobility. Electric vehicles fall into four categories:

– Hybrid Electric Vehicles (HEV), which run primarily on gasoline with a small battery assisting the internal combustion engine.
– Plug-in Hybrid Electric Vehicles (PHEV), which run on both gasoline and Diesel independently and electricity.
– Battery Electric Vehicles (BEVs) that are powered solely by electricity.
– Fuel Cell Electric Vehicles (FCEVs) which are powered by hydrogen.

Figure 1 compares various types of electric vehicles based on their energy source, consumption, and emissions from exhaust pipes and power plants.

Weiss et al. [23] suggest that battery electric vehicles with high battery capacity can produce between two and three times more greenhouse gases than hybrid electric vehicles, depending on the electricity source and the timing of the battery electric vehicles charging [10].

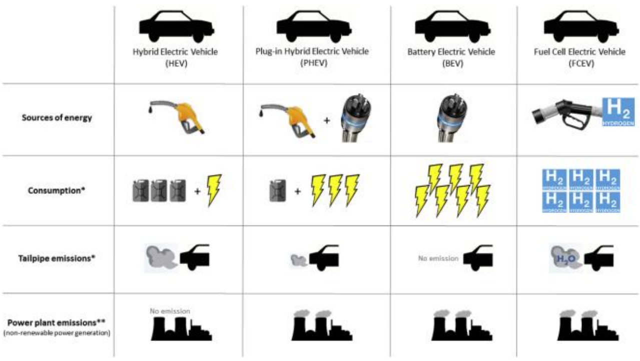

Fig. 1. Comparison of source and energy consumption and tailpipe emissions and energy generation for different types of electric vehicles (EV) [22] (*) The data displayed here is intended to be seen, not analysed. It is not organized or measured in any particular way; **) The technology used by each plant may differ, so we have not supplied numerical data for visualization [22]

The energy mix in Poland is based mainly on fossil fuels. However, a slight increase in the share of renewable sources is noticeable, whereas it is still a small share of the entire energy mix (Fig. 2) [23].

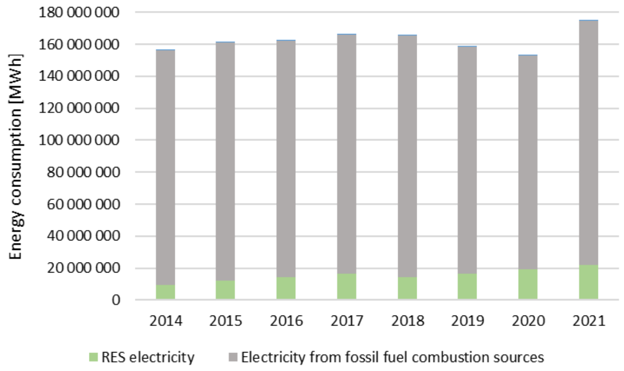

Fig. 2. Polish energy mix (based on [1])

It is apparent that the environmental effects of electric vehicles vary based on the particular circumstances.

Some studies have only concentrated on specific emission chains, including production [11], energy generation [9, 22] and operation [6]. To this end, there is an urgent need for a thorough review of literature studies that can help fully assess the environmental aspects of electric vehicles (EVs), given the issue's complexity and scope. This study is a step in that direction.

2. Materials and Methods

This article examines the emissions of harmful substances given off by different types of vehicles, including conventional internal combustion engine vehicles (ICEV), hybrids, plug-in hybrids, and battery electric vehicles (BEV). It looks at the emissions from different types of passenger cars, such as minis, smalls, mediums and large SUVs and executives, by comparing them in pairs.

The authors employed the COPERT (COmputer Programme to calculate Emissions from Road Transport) software for simulating emissions of internal combustion engines vehicles and energy consumption by battery electric vehicles. The methodology followed the guidelines set out by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019 [16], which are basic guidelines for inventories of greenhouse gases and air pollutants.

The equivalent emissions from battery electric vehicles were calculated from the formula given below (1):

$$\mathrm{E_i} = \mathrm{E}_c \times \mathrm{EF_i} \times \mathrm{M} \tag{1}$$

where: E_i – emission of pollutant i [g/km], E_c – the amount of electric energy used, measured [Wh], EF_i – emission factor of pollutant i for electricity produced by installations for combustion of fuels [g/Wh] based on [23], M – distance driven by vehicle [km].

Two types of simulations were carried out:

– comparison of emissions for BEV, hybrid, PHEV, and ICE vehicles
– comparison of emission equivalent with BEV for various energy mixes, based on indicators determined in the National Centre for Emissions Management (KOBiZE) studies [1].

Simulations were carried out, assuming that vehicles from each type of passenger cars travelled 10,000 km in each segment of passenger cars (Mini, Small, Medium and Large-SUV-Executive).

3. Results

Figures 3–22 show the influence of the vehicle type on emissions. The dependence is presented for each segment of passenger cars (Mini, Small, Medium and Large-SUV-Executive).

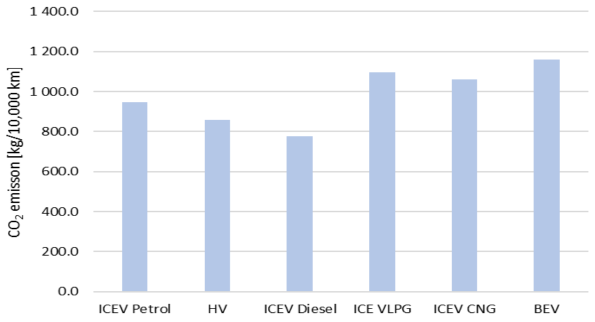

Fig. 3. Comparison of carbon dioxide (CO_2) emissions for the selection of Mini Passenger cars

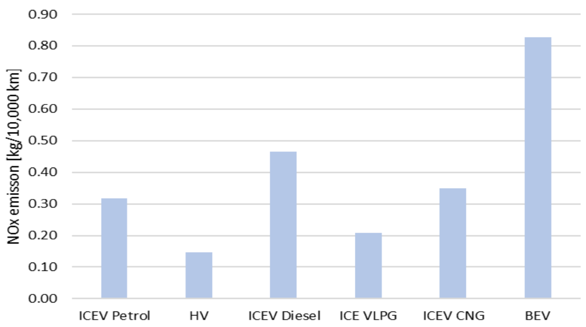

Fig. 4. Comparison of nitrogen oxides (NO_x) emissions for the selection of Mini Passenger cars

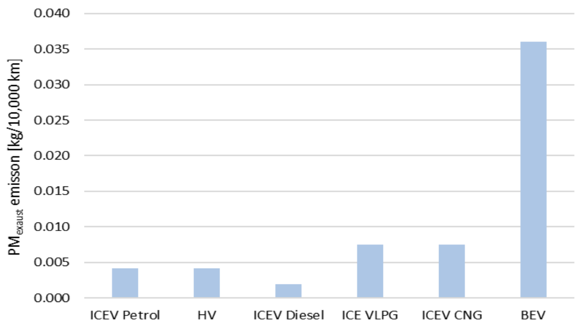

Fig. 5. Comparison of exhaust particulate matter (PM_{exh}) emissions for the selection of Mini Passenger cars

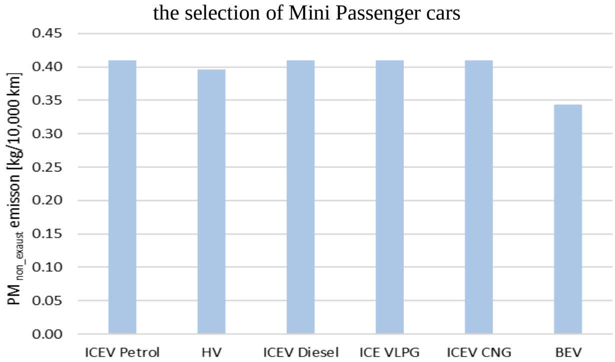

Fig. 6. Comparison of non-exhaust particulate matter ($PM_{non\text{-}exh}$) emissions for the selection of Mini Passenger cars

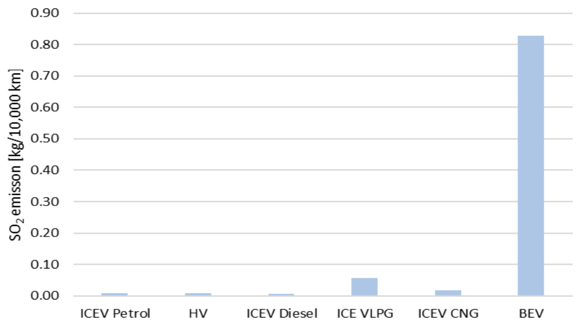

Fig. 7. Comparison of sulphur dioxide (SO_2) emissions for the selection of Mini Passenger cars

The simulation results presented in Fig. 3–22 show that, for the passenger car in the Mini segment, the equivalent emissions of CO_2, NO_x, PM_{exh} (PM emission from the exhaust system) and SO_2 are higher for battery electric vehicles than for internal combustion engines vehicles. The most significant difference can be seen for SO_2, PM_{exh} and NO_x. The simulations also show that in the case of the Mini segment, CO_2 and PM_{exh} emissions are the lowest for diesel internal combustion engines. In the case of NOx emissions, hybrid vehicles (HVs) and internal combustion engines LPG have the lowest emissions.

However, concerning $PM_{non\text{-}exh}$ emissions, it can be seen that the lowest emissions are from battery electric vehicles.

For the passenger car segment in the Small segment, similar to the Mini segment, the equivalent emissions of CO_2, NO_x, $PM_{exh,}$ and SO_2 are higher for battery electric vehicles than for vehicles with internal combustion engines.

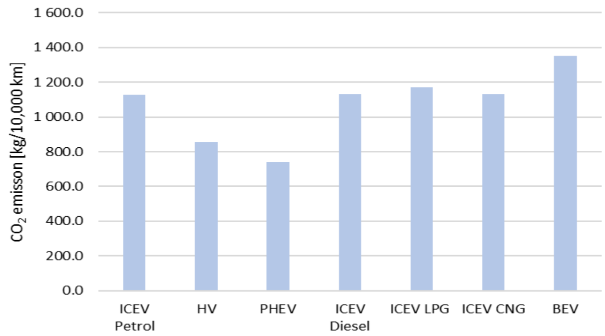

Fig. 8. Comparison of carbon dioxide (CO_2) emissions for the selection of Small Passenger cars

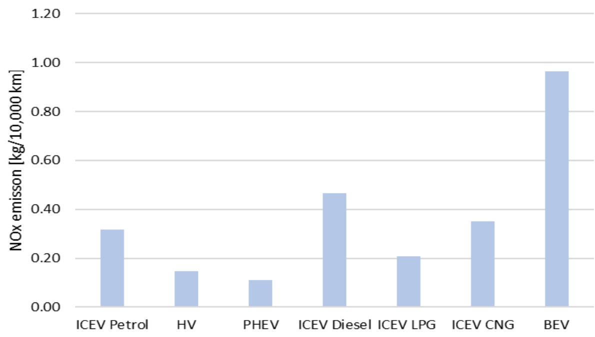

Fig. 9. Comparison of nitrogen oxides (NO_x) emissions for the selection of Small Passenger cars

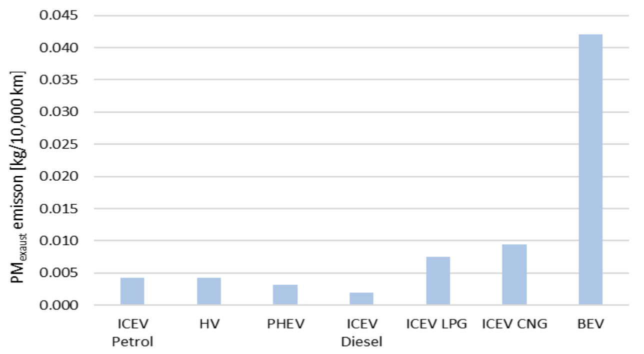

Fig. 10. Comparison of exhaust particulate matter (PM_{exh}) emissions for the selection of Small Passenger cars

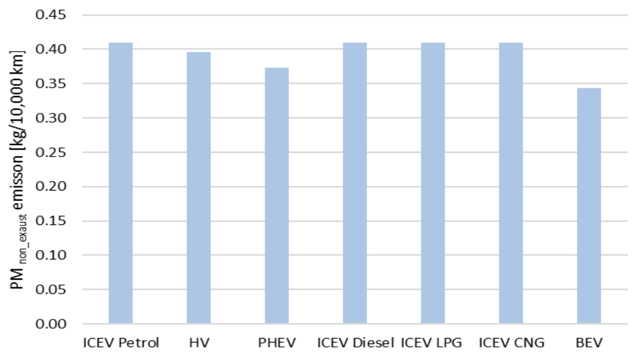

Fig. 11. Comparison of non-exhaust particulate matter ($PM_{non-exh}$) emissions for the selection of Small Passenger cars

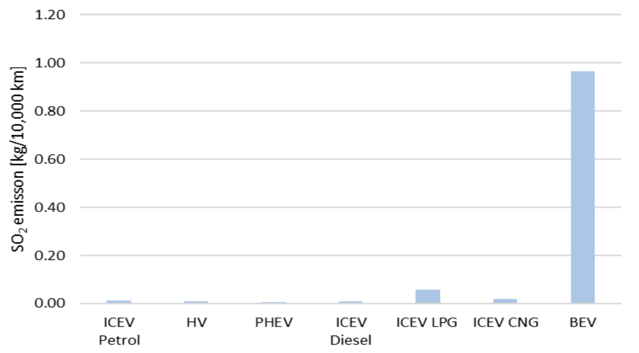

Fig. 12. Comparison of CO_2, NO_x, PM and SO_2 emissions for the selection of Small Passenger cars

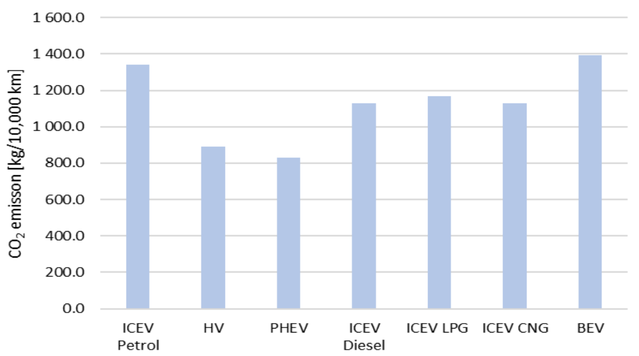

Fig. 13. Comparison of carbon dioxide (CO_2) emissions for the selection of Medium Passenger cars

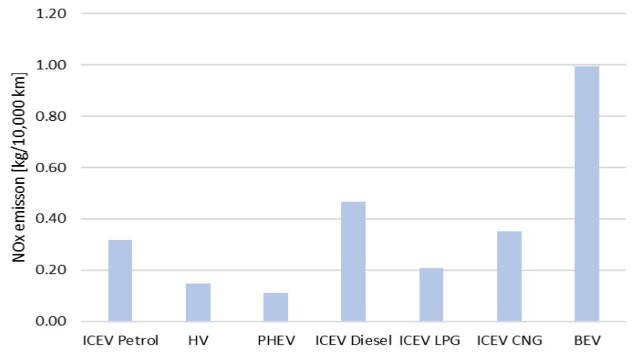

Fig. 14. Comparison of nitrogen oxides (NO_x) emissions for the selection of Medium Passenger cars

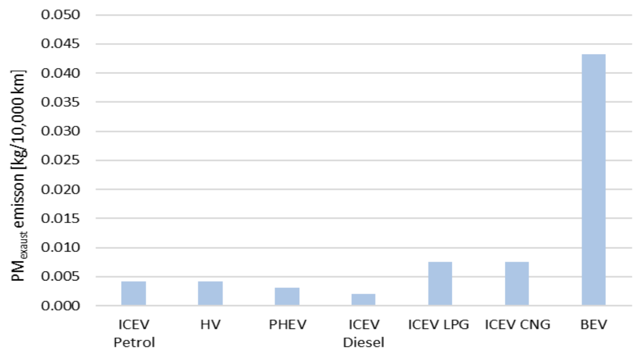

Fig. 15. Comparison of exhaust particulate matter (PM_{exh}) emissions for the selection of Medium Passenger cars

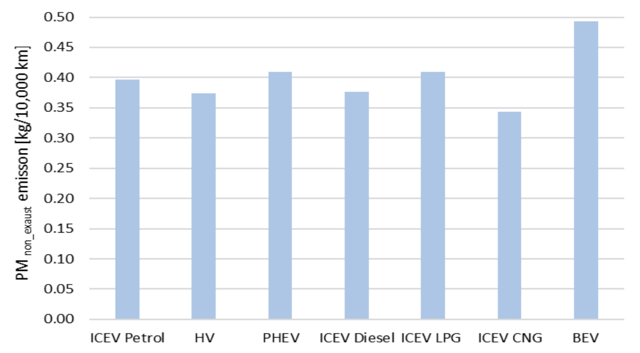

Fig. 16. Comparison of non-exhaust particulate matter ($PM_{non-exh}$) emissions for the selection of Medium Passenger cars

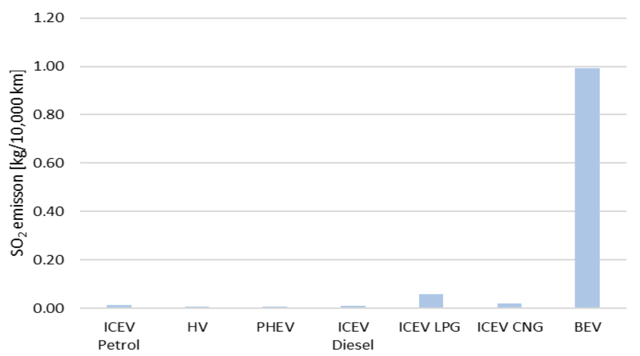

Fig. 17. Comparison of sulphur dioxide (SO_2) emissions for the selection of Medium Passenger cars

The simulations also show that in the Small segment, Plug-in Hybrid Electric Vehicles (PHEV) has the lowest CO_2, PM_{exh}, and NO_x emissions. As in the case of the Mini segment, in the case of PM emissions from abrasion, it can be seen that the lowest emissions are from battery electric vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV).

For the passenger car in the Medium segment, similarly to the previous segments (Mini and Small), the equivalent emissions of CO_2, NO_x, PM_{exh} and $PM_{non\text{-}exh}$ (PM emission from the tribological process) and SO_2 are higher for battery electric vehicles than for internal combustion engines vehicles.

The simulations also show that CO, NO_x and $PM_{non\text{-}exh}$ emissions are the lowest for separate Plug-in Hybrid Electric Vehicles.

In the case of non-exhaust PM emissions, contrary to the Mini and Small segments, the lowest emissions are for CNG internal combustion engines passenger cars.

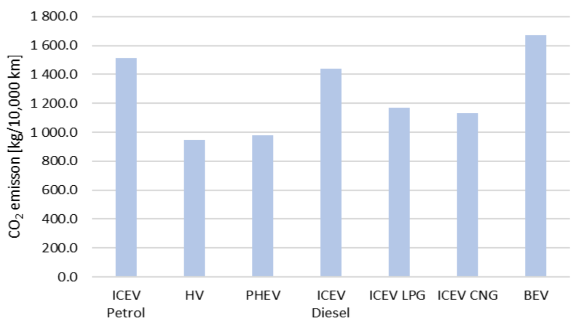

Fig. 18. Comparison of carbon dioxide (CO_2) emissions for the selection of Large-SUV-Executive Passenger cars

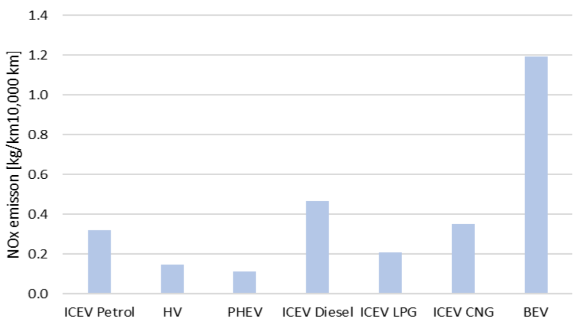

Fig. 19. Comparison of nitrogen oxides (NO_x) emissions for the selection of Large-SUV-Executive Passenger cars

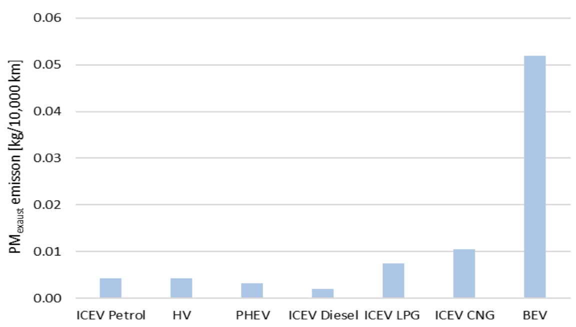

Fig. 20. Comparison of exhaust particulate matter (PM_{exh}) emissions for the selection of Large-SUV-Executive Passenger cars

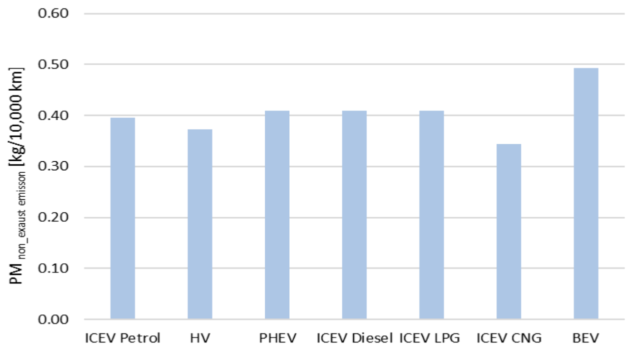

Fig. 21. Comparison of non-exhaust particulate matter ($PM_{non\text{-}exh}$) emissions for the selection of Large-SUV-Executive Passenger cars

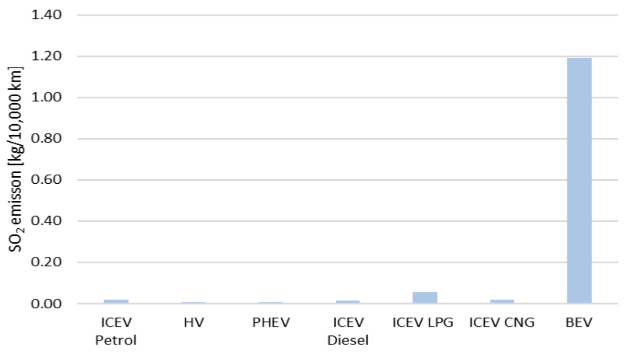

Fig. 22. Comparison of sulphur dioxide (SO_2) emissions for the selection of Large-SUV-Executive Passenger cars

For the passenger car in the Large-SUV-Executive segment, similar to the Medium passenger cars, the equivalent emissions of CO_2, NO_x, PM_{exh} and $PM_{non\text{-}exh}$ and SO_2 are higher for battery electric vehicles than for internal combustion engine vehicles.

The simulations also show that CO_2, NO_x and $PM_{non\text{-}exh}$ emissions are the lowest for separate Plug-in Hybrid Electric Vehicles (PHEV).

In the case of non-exhaust PM emissions, similarly to the Medium segments, the lowest emissions are for CNG internal combustion engines passenger cars.

Figures 23–25 show the influence of energy mix on emissions from battery electric vehicles. The dependence is presented for each segment of battery electric vehicles (Mini, Small, Medium and Large-SUV-Executive).

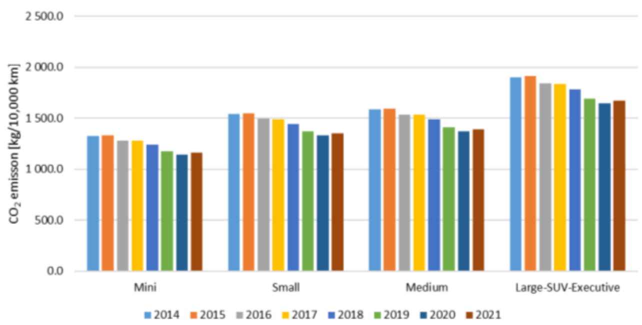

Fig. 23. Comparison of carbon dioxide (CO_2) emissions for BEV depending on polish fuel mix

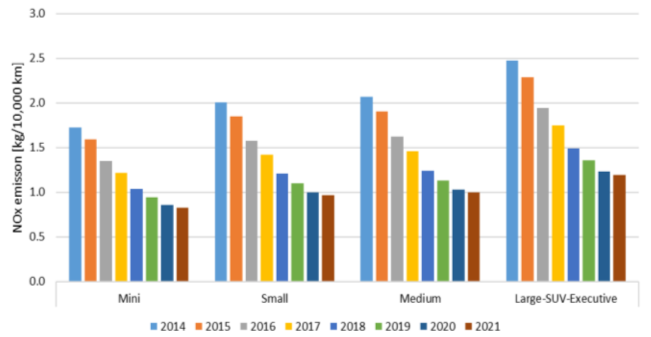

Fig. 24. Comparison of nitrogen oxides (NO_x) emissions for BEV depending on polish fuel mix

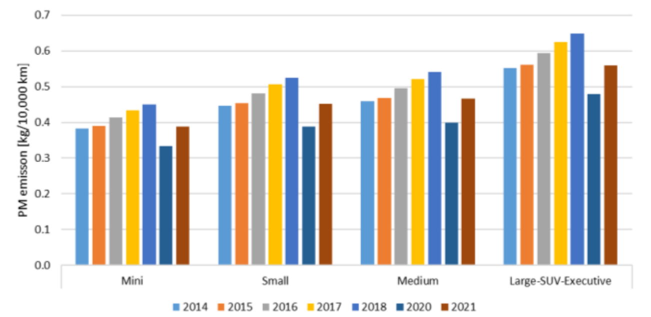

Fig. 25. Comparison of particulate matter (PM) emissions for BEV depending on polish fuel mix

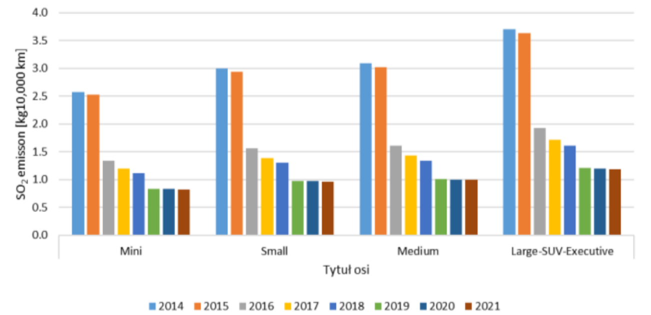

Fig. 26. Comparison of sulphur dioxide (SO_2) emissions for BEV depending on polish fuel mix

Figures 23–25 shows the dependence of equivalent emissions on the energy mix. It can be seen that as Renewable Energy Sources (RES) electricity increases, the equivalent emissions from electric vehicles decrease. For 2020, the share of RES electricity in total electricity production was the highest, almost 12.5%, while for other years, it was approximately 10%.

4. Conclusions

Research conducted and the data presented in the article indicate that the amount of carbon dioxide and pollutants released by cars is largely dependent on the kind of fuel used (in the case of ICEVs) and the energy mix (for BEVs).

Simulation studies conducted in Poland suggest that introducing electric cars to traffic while removing cars with internal combustion engines is not necessarily beneficial.

The simulation results shown in Fig. 3–22 show that the CO_2 emissions of battery electric vehicles are higher than those of internal combustion engine vehicles for all segments (Mini, Small, Medium and Large-SUV-Executive.

The same is true for NO_x, exhaust PM and SO_2 emissions. The SO_2 emissions from battery electric vehicles are significantly higher than those from internal combustion engines because the energy mix is mainly based on coal. Only the non-exhaust emission PM (tire, brake wear and abrasion), is lower for battery electric vehicles, but this difference is negligible.

Figures 23–25 compares CO_2, NO_x, PM and SO_2 emissions for battery electric vehicles depending on the Polish fuel mixture. It shows that the emission depends on the energy mix. Comparing the values in Fig. 2 with the simulation results, it can be seen that the greater the share of renewable sources in the energy mix, the lower the emission of all pollutants under consideration. This relationship clearly shows that if Poland strives for climate neutrality, it should increase the share of renewable sources in the energy mix before decarbonizing transport.

In conclusion, the findings of the research and the evaluation of the sources demonstrate that, with the existing energy mix in Poland, the shift of more cars to electric engines and a decrease in the number of cars with internal combustion engines will not have a beneficial effect on the environment and human health, as the amount of NO_x and SO_2 in the atmosphere will escalate.

This article serves as a benchmark for further exploration into the role of electromobility in the energy mix or electricity industry. The purpose of the study could be to examine the effects of electromobility on the environment and the economy. It is plausible to apply the benchmarking system that is provided to cars powered by alternate fuel sources, such as hydrogen.

Nomenclature

BEV	battery electric vehicles
CO_2	carbon dioxide
EV	electric vehicles
FCEV	fuel cell electric vehicles
GHG	greenhouse gases
HEV	hybrid electric vehicles
ICEV	internal combustion engine vehicles
NO_x	nitrogen oxides
PHEV	plug-in hybrid electric vehicles
PM	particulate matter
RES	renewable energy sources
SO_2	sulphur dioxide

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