

Article

The Influence of Power Sources for Charging the Batteries of Electric Cars on CO₂ Emissions during Daily Driving: A Case Study from Poland

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Abstract: The main sources of greenhouse gas emissions and air pollution from the transport sector are diesel- and gasoline-powered passenger cars. The combustion of large amounts of conventional fuels by cars contributes to a significant release of various compounds into the atmosphere, such as solid particles, nitrogen oxides, carbon monoxide, and carbon dioxide. In order to reduce these pollutants in places of their high concentration (especially in urban agglomerations), the use of ecological means of transport for daily driving is highly recommended. Electric vehicles (EV) are characterized by ecological potential due to their lack of direct emissions and low noise. However, in Poland and many other countries, electricity production is still based on fossil fuels which can significantly influence the indirect emissions of carbon dioxide into the atmosphere associated with battery charging. Thus, indirect emissions from electric cars may be comparable or even higher than direct emissions related to the use of traditional cars. Therefore, the aim of the work was to analyze the amount of carbon dioxide emissions associated with the use of electric vehicles for daily driving (City, Sedan, SUV) and their impact on the environment on a local and global scale. Based on the assumed daily number of kilometers driven by the vehicle and the collected certified catalog data (Car Info Nordic AB), the direct emissions generated by the internal combustion engines (ICE) were calculated for specific cars. These values were compared to the indirect emissions related to the source of electricity generation, for the calculation of which the CO₂ emission coefficient for a particular energy source and energy mix was used, as well as reference values of electricity generation efficiency in a given combustion installation, in accordance with the KOBiZE (The National Centre for Emissions Management) and European Union regulation. Indirect emissions generated from non-renewable fuels (lignite, hard coal, natural gas, diesel oil, heating oil, municipal waste) and renewable emissions (wind energy, solar energy, hydro energy, biomass, biogas) were considered. The results indicated that for the Polish case study, indirect carbon dioxide emission associated with the daily driving of EV (distance of 26 km) ranges 2.49–3.28 kgCO₂·day⁻¹. As a result, this indirect emission can be even higher than direct emissions associated with ICE usage (2.55–5.64 kgCO₂·day⁻¹).

Keywords: CO₂ emission; daily driving; indirect emission; direct emission; electric car

1. Introduction

One of the key objectives of the European Union's climate and energy policy is to reduce greenhouse gases (GHG) emissions by at least 40% by 2030, compared to 1990 [1]. To do this, the focus should be on reducing GHG emissions from the highest emission sectors, which include energy supply,

industry, and transport. However, compared to 1990, GHG emissions from energy supply and industry are gradually decreasing. By 2017, emissions from these sectors were reduced by 32% and 35%. The situation is slightly different in the case of the transport sector. During the same period, GHG emissions (especially carbon dioxide) increased by 19%, and from 2013 onwards, a steady upward trend can be observed [2].

One of the main factors responsible for GHG emissions from the transport sector is road transport, responsible for 71.7% of emissions, where the largest share of emissions are passenger cars [3]. The reasons for which most people decide to use passenger cars is the desire to become independent of public transport, shorter travel time, associated with direct reach of the destination, and driving comfort [4]. In addition, the increase in competitiveness on the automotive market has meant that the car is no longer just a luxury good, but a product available to every social group, which causes a significant increase in their number. As a result, the rapidly growing number of cars, in addition to carbon dioxide and other GHG emissions, brings many undesirable environmental effects. The use of cars with conventional internal combustion engines (ICE), which constitute the vast majority in the European Union (EU) [5], contributes to the increasing emission of air pollutants, which are a particular threat to human health and life [6]. These are not only compounds that are components of car exhaust gases—carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) [7], but also particulate matter PM10 and PM2.5, resulting from the abrasion of asphalt and car tires [8]. Such a high concentration of GHG and air pollutants from the transport sector forces measures to reduce substances harmful to the environment.

The paper is structured as follows: Section 2 explains the theoretical basis of the work associated with the presentation of electric vehicles, indirect emissions associated with the source of electricity production and explanations of the case study. Section 3 presents the methodology related to the ecological and sensitivity analysis and the data used for the calculations. Section 4 includes the results analysis and their detailed discussion. The conclusions and future works are presented in Section 5.

2. Theoretical Background

2.1. Electric Vehicles

A certain alternative to conventional vehicles is the use electric cars. An electric vehicle in its basic meaning can be understood as an automobile with an electric motor connected to the wheels through a gearbox with one or two speeds [9]. Currently, there are many types of electric vehicles on the market. The most popular types include the battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), and range extended electric vehicle (REEV). The BEV is a fully electric vehicle, in which there is no internal combustion engine, and the electric unit is responsible for driving the car and the powering of on-board devices. The PHEV is a vehicle based on an internal combustion engine supplemented with an electric motor. Whereas, the REEV is a vehicle in which the electric motor is the main power unit. The REEV is equipped with an internal combustion engine (ICE) that switches on only when it is necessary to generate energy to charge the battery, providing electric drive.

Due to the ecological potential of electric vehicles (EV), their wide use instead of internal combustion engine (ICE) vehicles can be beneficial for the climate and the environment [10,11]. The biggest advantages of electric cars are primarily zero direct emissions from the drive unit [12–14], lower operating costs [13,15] and low operational noise levels [16,17]. The positive reception of public opinion is also an important element [18]. On the other hand, negative aspects of using EV include short-range and long charging time [19,20], limited number of charging stations [21], and a high share of the battery price in the costs of the vehicle [22], the replacement of which involve additional, significant investment.

2.2. The Use of EV and Indirect Emissions Associated with the Source of Electricity Production

The development of electro mobility on both a local and global scale may be one of the most key decisions for achieving a sustainable energy future [23]. Anthony Jnr et al. [24] indicated that the development of electric mobility as a service, bringing together different electric means of transport (cars, bicycles, etc.) is one of the solutions combining the possibility of alleviating environmental issues while improving transport at the same time. Such action may be particularly helpful in the case of designing complex transport architecture for technologically advanced cities (smart cities) [25]. However, in order to fully consider the potential for EV reduction by CO₂, the specific aspects of generating electricity at a given location should be identified. Compared to traditional ICE cars, which are powered solely by diesel or unleaded gasoline, the electricity for EV charging can be generated from various energy sources—conventional (e.g., lignite, coal, natural gas) and renewable (e.g., biomass, biogas, solar energy, wind energy, hydro energy). Although the electric cars during their daily driving do not generate any pollution directly into the atmosphere, they can significantly contribute to the generation of indirect emissions associated with the source of electricity for battery charging [26]. A lot of work has been done in recent years to show the real impact of energy production on the environmental performance of EV [27–30]. Hacker [31] showed that depending on the diversity of sources in domestic electricity production, the average emission index, describing the actual amount of carbon dioxide emitted to the atmosphere per unit of energy produced, is characterized by high variety, but fossil fuels have the highest emission. Admittedly, Krause et al. [32] reported that strong electrification of the car fleet can be a significant potential in reducing CO₂ emissions, if the electricity generated for batteries charging comes primarily from low-carbon sources.

The most favorable, from an ecological point of view, is charging the batteries with renewable energy. The production of electric energy, however, depends on the country and is highly diversified in the European Union (Figure 1). As a result, the development of electro mobility in countries with a dominant share of fossil fuels in electricity generation may prove controversial.

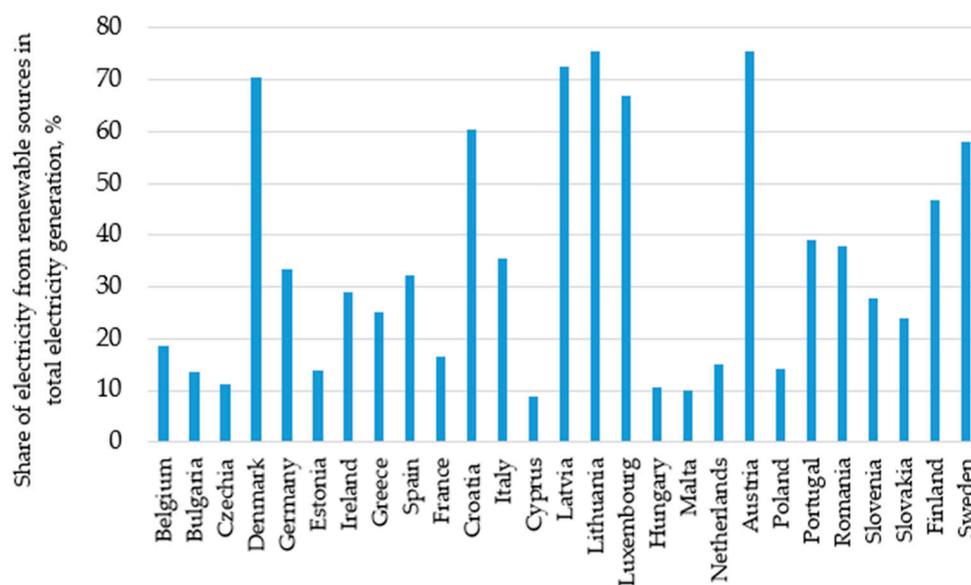


Figure 1. Share of electricity from renewable sources in total electricity generation in EU-27 in 2017 [33].

2.3. Related Works

There are also several studies in the literature that compare the indirect EV emissions associated with the source of electricity generation in relation to a specific case study, using different methods. These cases are summarized in Table 1.

Table 1. Main case studies in the literature.

Authors	Aim	Methodology	Context
Holdway et al. [34]	Analyze indirect CO ₂ emission related to the source of electricity production and the comparison to direct emissions of the ICE car and Hybrid electric vehicles (HEV).	The average CO ₂ emissions from electricity generation, Average well-to-wheels CO ₂ emissions for EV	US, UK and France Case Studies
Williams [35]	Analyze indirect CO ₂ emission related to the source of electricity production and the comparison to direct emissions of the ICE car and Hybrid electric vehicles (HEV).	The average CO ₂ emissions from electricity generation, Average well-to-wheels CO ₂ emissions for EV	US, China, Japan, India, Germany, Russia, Brazil, UK, France, Italy, Mexico, South Korea, Spain, Canada, Indonesia Case Studies
Kurien and Srivastava [36]	Detailed analysis of the emission threat of EV depending on the scenarios and vehicle category	Average CO ₂ emissions from EV calculated by referencing the electric power consumed by the vehicle per kilometer and the CO ₂ emissions during electricity generation	India Case Study
Pan et al. [37]	Comprehensive analysis of the widespread use of EVs depending on the electricity sources in a specific country	AGT method	Sweden, US, China, France Case Studies
Wolfram and Wiedmann [38]	Analysis of the environmental performance of various types of vehicles in terms of GHG reduction depending on the share of renewable energy sources	LCA method	Australia Case Study

Holdway et al. [34], calculated average CO₂ emissions based on the amount of CO₂ produced and the electricity generated in the grid. In addition, they included for each EV in each country well-to-power-plant emissions, using fuel efficiency data, the breakdown of total net electricity generation and the well-to-power-plant emissions for each type of fuel used in electricity generation. They used this data to describe a case study from the US, UK, and France. A similar methodology was used by Williams [35], with case studies being extended to 15 countries. Similarly, calculations for the Indian case study were used by Kurien and Srivastava [36], analyzing the EV emissivity from different scenarios. A slightly different simulation for case studies from Sweden, the US, China, and France was developed by Pan et al. [37]. In order to comprehensively analyze the possibility of implementing transport electrification for a specific country, the authors decided to use the innovative AGT method, combining the AHP, Gray Relation Grade Analysis and TOPSIS methods. In turn, Wolfram and Wiedmann [38], for the Australian case study, used the LCA methodology to analyze the environmental performance of EVs depending on the percentage share of renewable energy sources in electricity production.

However, in the literature there is no study focusing in detail on the problem of implementing electrification of transport, when electricity production will still rely on coal. In fact, in the case of India [36], the problem of generating electricity from coal partially meets this criterion, but the fast transformation of the energy system in that country reduces the use of solid fuels as energy sources. Kurien and Srivastava [36] considered that in 2022, the share of renewable energy sources in electricity production in India will increase to 51%. Therefore, it seems crucial to consider a case study with a slower abandonment of hard coal and lignite in favor of renewable energy sources. There are also no case studies included Poland, which has its own very large resources of coal.

2.4. Poland as a Case Study

An example of a country in the European Union, whose production of electricity is based mostly on solid fossil fuels is Poland (Figure 2), which mainly uses hard coal and lignite [39]. Over the past few decades, the Polish power industry has produced over 80% of electricity from both of these raw materials. Although European Union regulations and low-carbon economy are oriented to electricity production from renewable energy sources and biofuels, in Poland it is still a definite minority. Additionally, the process of abandoning coal energy in Poland will not be as fast as in other countries. Due to the high installed power of electricity and the high level of employment in the coal sector, it should still be expected that in the coming years, lignite and hard coal will be Poland's main raw materials in electricity production. The Ministry of Energy in Poland estimates that in 2030, both raw materials will still be responsible for the production of 56–60% of electricity [40]. It is only in 2040 that a significant decrease in the share of coal in electricity generation should be expected, although this is still an uncertain scenario. Many studies showed that domestic electricity production, when coal is the main source, has a harmful effect on the natural environment, which is associated primarily with high emissions of carbon dioxide and other air pollutants [41–44]. As a result, using an electric car in Poland, with the batteries charging with energy from the commercial power grid, will not provide zero emission. In this situation, the development of electro mobility in Poland might be considered controversial and treated with due caution. In fact, the problem of concentration of air pollutants in urban agglomerations can be significantly eliminated but it will not contribute to reducing the amount of pollutants in the overall balance, due to the only change in the place of emission of harmful compounds. Despite the fact that the geospatial effects of changing the place of CO₂ emissions from populated to uninhabited places may have a positive effect even for the health of residents, the amount of emissions into the atmosphere will remain unchanged. Additionally, among the European Union countries, Polish cities are among the worst for air quality, which is confirmed by the latest European Environment Agency (EEA) report [45]. This problem is mainly due to low emissions, which is also exacerbated by road transport. Such action leads to numerous social conflicts, which requires urgent changes in the scope of national and international climate policy.

The main aim of the work was to analyze the Polish case study of the environmental performance of the EV during the daily driving depending on the energy source for electricity production to charge the car batteries, and to compare the results with the emission of pollutants when using vehicles with the internal combustion engine. Additionally, the sensitivity analysis concerning the influence of the renewable energy share in Polish energy mix on the reduction of CO₂ emission was considered, as well.

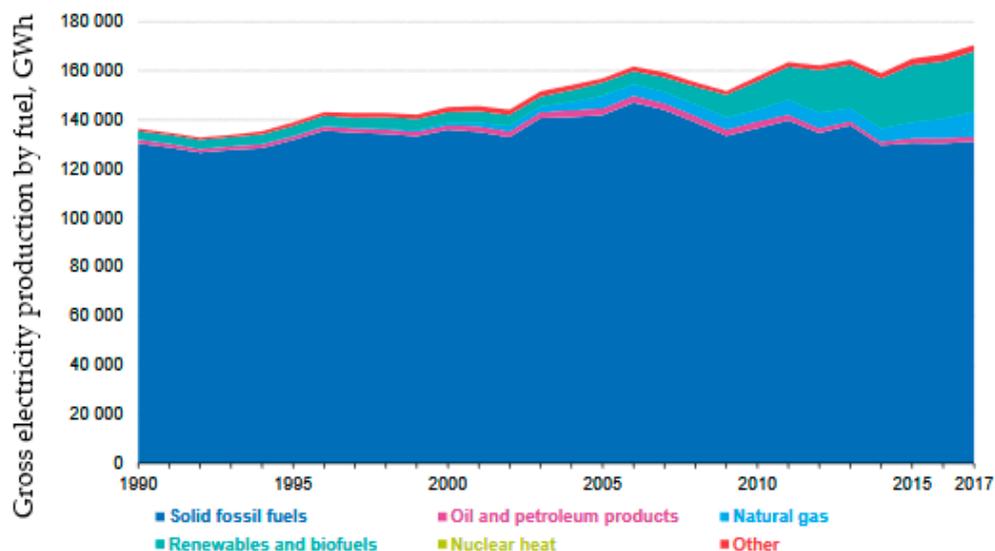


Figure 2. Gross electricity production by fuel in Poland [33].

3. Materials and Methods

3.1. Cars Used in the Experiments and Data Collection

In the research, the cars powered by various types of fuel, such as gasoline, diesel, and electricity were considered. As a result, the nine vehicles were selected. The vehicles belonged to the three classes: city, sedan, and SUV. The engine power for each car in the specified category was the same. The main characteristics of the cars are presented in Table 2.

Table 2. Main car investigated in the research specifications [46].

Vehicle		Engine Power	Fuel	Curb Weight	Maximum Torque	CO ₂ Emission	Combined Fuel Consumption
		kW		kg	Nm	g·km ⁻¹	* kWh·100 km ⁻¹ or dm ³ ·100 km ⁻¹
City	Mini Cooper D Manual	80	Diesel	1180	240	104	3.9
	Kia Rio 1.4 CVVT	80	Gasoline	1165	137	127	5.5
	Renault ZOE R110 41 kWh	80	Electricity	1500	225	0	* 15.95
Sedan	Fiat Tipo Station Wagon 1.6 Multijet Manual	88	Diesel	1395	300	98	3.7
	Mazda 3 Sport 2.0 SKYACTIV-G Manual	88	Gasoline	1200	210	119	5.1
	Hyundai Ioniq Electric 28 kWh	88	Electricity	1495	295	0	* 12.5
SUV	Kia Sportage 1.6 CRDi AWD DCT	100	Diesel	1825	320	138	6.4
	Chevrolet Captiva 2.4 Manual	100	Gasoline	1665	220	217	8.9
	Peugeot e-2008	100	Electricity	1548	260	0	* 16.5

* concern EVs (electricity demand per 100 km).

3.2. Ecological Analysis

In order to analyze the environmental impact of electric vehicles (EV) and to compare the results with conventional internal combustion engines (ICE), it was assumed that the daily distance covered by each car amounts to 26 km [47]. For the purposes of the analysis, this value was averaged, but there are many second-order effects that directly affect the behavior of drivers in relation to vehicle kilometers of travel (VKT), such as the impact of the fuel tax, and socio-economic and demographic factors [48]. The main idea of the work was to compare only emissions associated with the process of vehicle operation (daily driving). As the cars' (EV and ICE), fuels, and other devices can be produced in different countries and with a different electricity mix, the CO₂ emissions related to this process were also excluded from the analysis. In the case of cars with an ICE, only direct emissions related to fuel consumption (combustion) were taken into account, while in the case of the EV, indirect emissions related to the production of electricity for battery charging were considered. These limitations led to focus the attention on the problem of electric cars' application and their indirect impact on the environment in Poland, a country still dominated by coal usage. The environmental analysis included parameters such as: the daily CO₂ emission compared to car use (M_{CO_2}), the CO₂ emission value depending on the source of electricity generation (M_{REC-CO_2}), the amount of daily energy consumed by the EV, and the daily CO₂ emission related to the use of the electric vehicle (M_{D-CO_2}).

The daily value of carbon dioxide emissions into the atmosphere, generated by using cars, was calculated according to the formula:

$$M_{CO_2} = M_{CAT-CO_2} \cdot L \quad (1)$$

where: M_{CO_2} —daily carbon dioxide emissions into the atmosphere, generated by using cars ($kg \cdot day^{-1}$); M_{CAT-CO_2} —catalogue value of carbon dioxide emissions to the atmosphere ($kg \cdot km^{-1}$), L —daily distance covered by cars ($km \cdot day^{-1}$).

The amount of actual carbon dioxide emissions generated to charge the electric car batteries, resulting from the complete combustion of fuels and introduced directly or indirectly into the environment by the electricity generating installation operating at rated parameters (Table 3), was calculated according to the formula [49]:

$$M_{REC-CO_2} = 360 \cdot \frac{We_{CO_2}}{\eta} \quad (2)$$

where: M_{REC-CO_2} —carbon dioxide emissions for the specified fuel ($kg \cdot MWh^{-1}$); We_{CO_2} —carbon dioxide emission coefficient for specified fuel or average carbon dioxide emission coefficient of a fuel mixture combusted in specified energy sources installations ($kg \cdot GJ^{-1}$); η —electricity generation efficiency in the specified fuel combustion installation (%).

The electricity demand by the EV was calculated using the equation:

$$E = L \cdot E_{CAT-E} \quad (3)$$

where: E —daily amount of energy consumed during the EV operation ($kWh \cdot day^{-1}$); E_{CAT-E} —catalogue value of the electric car's electricity consumption ($kWh \cdot km^{-1}$).

The daily amount of carbon dioxide emissions into the atmosphere, emitted during one day of operation of the electric vehicle, was calculated according to the formula:

$$M_{D-CO_2} = E \cdot \sum K_i \cdot M_{REC-CO_2} \quad (4)$$

where: M_{D-CO_2} —the amount of carbon dioxide emitted during one day of electric car operation (g); K_i —the share of given fuel in electricity production (%).

Table 3. We_{CO_2} coefficient and power plant efficiency depending on the type of fuel combusted [49,50].

Fuel		We_{CO_2}	η
		$kg \cdot GJ^{-1}$	%
Non-renewable	Hard coal	95.48	44.2
	Lignite	110.76	41.8
	Natural gas	56.1	52.5
	Diesel	74.1	44.2
	Heating oil	77.4	44.2
	Municipal waste	91.7	25.0
Renewable	Biogas	54.6	42.0
	Biomass	100	25.0
	Solar radiation energy	0	30.0
	Wind energy	0	30.0
	Hydro energy	0	30.0

3.3. Sensitivity Analysis

Due to the fact that, compared to individual fuels, the We_{CO_2} emission factor for energy mix from the grid varies (depending on the share of specified fuels in domestic electricity production), it was decided to carry out the sensitivity analysis. Sensitivity analysis was performed to investigate how the changes in the Polish energy mix can influence the negative or positive effect of the considered issue. With reference to the current value of the CO_2 emission factor for the Polish energy mix [51], the impact of changing the value of this factor on the environmental performance of the EV was determined, and

the obtained data was compared with direct emissions generated by the ICE, whose level is constant. The analysis was carried out separately for each of the car classes.

4. Results and Discussion

The daily direct emission of carbon dioxide generated by using EV and ICE and released into the atmosphere is shown in Figure 3. In order to determine it, the standard daily number of kilometers traveled by a vehicle (L) was multiplied (Formula (1)) with the catalog values of carbon dioxide emissions per kilometer M_{CAT-CO_2} , presented in Table 2, and determined in accordance with the certified car database Car Info Nordic AB.

In the case of the ICE, direct carbon dioxide emissions are comparable and within the range $2.55 \text{ kgCO}_2 \cdot \text{day}^{-1}$ and $3.30 \text{ kgCO}_2 \cdot \text{day}^{-1}$. This is in line with a common trend of the majority of car manufacturers focused on CO_2 emission reduction [52]. Among the car classes, the SUVs emit much more carbon dioxide into the atmosphere ($5.64 \text{ kgCO}_2 \cdot \text{day}^{-1}$ for gasoline, and $3.59 \text{ kgCO}_2 \cdot \text{day}^{-1}$ for diesel). It is associated with a significantly higher fuel consumption characterizing this model compared to vehicles from other classes [52,53]. The use of an EV does not generate direct CO_2 emissions [54,55].

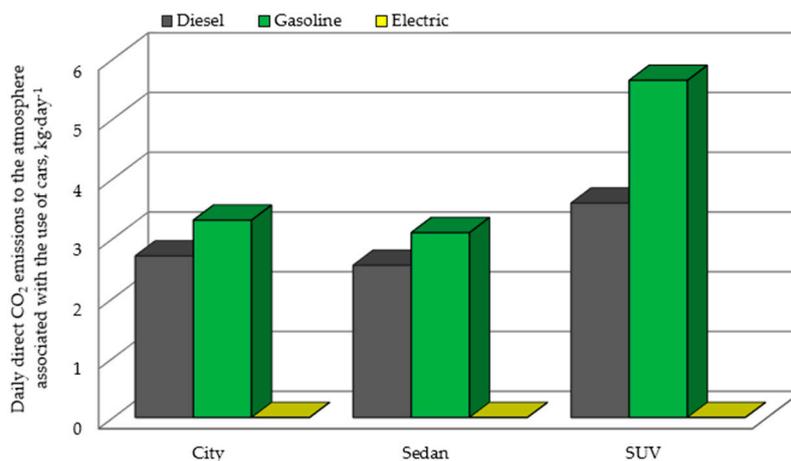


Figure 3. Daily direct CO_2 emissions to the atmosphere associated with the use of a car in the city (distance of 26 km) divided into City, Sedan, and SUV classes.

However, although the EVs do not generate direct emissions, they contribute significantly to the generation of indirect emissions associated with the source of electricity generated to charge the batteries [56,57]. The national power plant portfolio and specific power plants used to generate electricity in the process of charging batteries have a significant impact on the amount of carbon dioxide assigned to indirect emissions [58,59]. For countries such as Poland, where the majority of electricity is generated from fossil fuels, the electricity in the grid, which is a mixture of energy from various power plants, it is necessary to determine the indirect CO_2 emissions resulting from the combustion of specified/participated fuels. Depending on the fuel/energy source used, this emission is highly diversified (Figure 4).

The We_{CO_2} coefficients adopted in Table 3, determined for power plants in Poland are similar to those used in other countries [60–62]. Among the analyzed energy sources, the highest M_{REC-CO_2} emission is characterized by solid biomass ($1440 \text{ kgCO}_2 \cdot \text{MWh}^{-1}$). However, in this case, the overall balance of carbon dioxide emissions into the atmosphere is zero or insignificant, due to the equivalent amount of carbon dioxide absorbed by biomass during the plant's growing phase [63]. For other energy sources, the largest emission is characterized by electricity generated from municipal waste— $1320.5 \text{ kgCO}_2 \cdot \text{MWh}^{-1}$, lignite $953.91 \text{ kgCO}_2 \cdot \text{MWh}^{-1}$, and coal $777.76 \text{ kgCO}_2 \cdot \text{MWh}^{-1}$. Slightly lower emissions are from oils (heating oil: $630.51 \text{ kgCO}_2 \cdot \text{MWh}^{-1}$, diesel: $603.53 \text{ kgCO}_2 \cdot \text{MWh}^{-1}$), biogas ($468 \text{ kgCO}_2 \cdot \text{MWh}^{-1}$) and natural gas ($384.68 \text{ kgCO}_2 \cdot \text{MWh}^{-1}$). The CO_2 emission rate for energy

from the grid, which is a mixture of energy from various power plants, is relatively high and amounts to $765 \text{ kgCO}_2\text{-MWh}^{-1}$ [51]. The calculated emissions are very similar to emissions from power plants in other European countries [64,65]. Electricity production from the sun and wind does not generate any direct carbon dioxide emissions into the atmosphere. However, LCA analyses indicate that the average value of indirect emissions for electricity generation from the sun is $26 \text{ kgCO}_2\text{-MWh}^{-1}$, from hydro $11 \text{ kgCO}_2\text{-MWh}^{-1}$, and from wind $29 \text{ kgCO}_2\text{-MWh}^{-1}$, which is still much lower than for other energy sources [66].

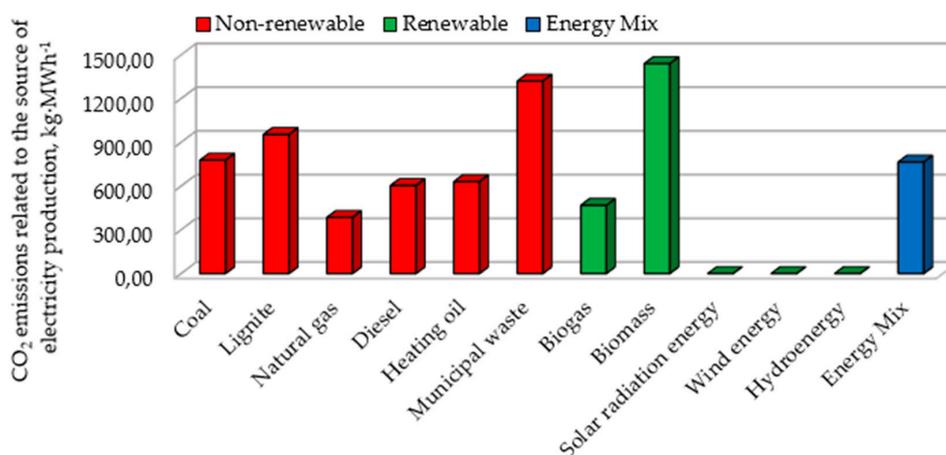


Figure 4. Carbon dioxide emissions depending on the source of electricity production.

Depending on the source of electricity, the EV may have carbon dioxide emissions comparable to the ICE. To this end, a comparison was made comparing the daily indirect emission, depending on the source of electricity production, used to charge the EV batteries, and the daily direct emission generated by cars with a gasoline and diesel engine. Formulas (2)–(4) are used to determine the indirect emissions related to the source of electricity production. Formula (2) was obtained in accordance with the information provided by the Polish Ministry of Energy, together with the CO₂ emission coefficient specified in Table 3. Reference power plant efficiency values for a given energy source, also contained in Table 3, were calculated by means of an EU regulation. Formula (3), determining the demand for daily electricity, results from the multiplication of the daily number of kilometers traveled by the vehicle (L) with the catalog values of electricity consumption during the use of the $E_{\text{CAT-CO}_2}$ vehicle, contained in Table 2, obtained in accordance with the certified car database Car Info Nordic AB. Equation (3), determining the final daily amount of indirect emission resulting from charging EV batteries, was calculated by multiplying the daily demand for electricity by EV, the share of a particular source in electricity production (for individual sources apart from the energy mix, 100% was assumed) and the indirect emission calculated in Formula (2) for a specified energy source.

Depending on the class, the EV may have a more positive or more negative ecological impact than traditional/conventional ICE cars (Figure 5). The results shown in Figure 5 revealed that for the Polish case study, charging batteries with electricity from the mains may be more harmful to the environment than using ICE cars. Although only in one case (City class) the indirect emission was higher than the direct emission, the differences were not very significant.

Electricity consumption also has a significant impact on the environmental performance of electric cars. The EV with high electricity consumption may turn out to be less eco-friendly than standard ICE cars. Among the analyzed classes, this is the case in the City class, where indirect emission, assuming battery charging from the grid, is higher ($3.17 \text{ kgCO}_2\text{-day}^{-1}$) than direct emission of diesel ($2.70 \text{ kgCO}_2\text{-day}^{-1}$) and lower than direct emission of gasoline cars ($3.30 \text{ kgCO}_2\text{-day}^{-1}$). In the other classes, indirect emissions for the energy mix are lower than direct emission from diesel cars and from gasoline cars. However, these differences are not significant enough to sufficiently reduce carbon dioxide emissions into the atmosphere. In the Sedan class, direct diesel emissions were only $0.06 \text{ kgCO}_2\text{-day}^{-1}$

higher than indirect EV emissions (and in the case of gasoline— $0.6 \text{ kgCO}_2 \cdot \text{day}^{-1}$). A more substantial difference was recorded in the SUV class—indirect emissions were by $2.36 \text{ kgCO}_2 \cdot \text{day}^{-1}$ lower than direct emissions of a gasoline car, but still characterized by high carbon dioxide emissions into the atmosphere ($3.28 \text{ kgCO}_2 \cdot \text{day}^{-1}$).

The presented results are in accordance with the literature. Depending on the national energy mix and source of electricity, the EV may be more harmful to the environment [33,34]. The use of electric cars does not ensure zero emissions. Certainly, their advantage is that they do not emit direct pollutants into the atmosphere, minimizing the accumulation of pollutants from the transport sector, particularly in urban agglomerations. However, the overall balance of carbon dioxide emissions is not being reduced. Only the place of emission of harmful pollutants is changing.

The situation is worst when the electricity used to charge the electric car battery comes from power plants burning municipal waste. Then, the EV turns out to generate nearly twice as much CO_2 emissions as cars with internal combustion engines. However, the percentage share of such power plants in electricity generation is negligible, both in Poland [67] and in other European countries [68]. The coal-fired and lignite-fired power plants, which constitute 70% of the total share in electricity production in Poland, also cause high pollution. In this case, the development of electro mobility seems to be very controversial.

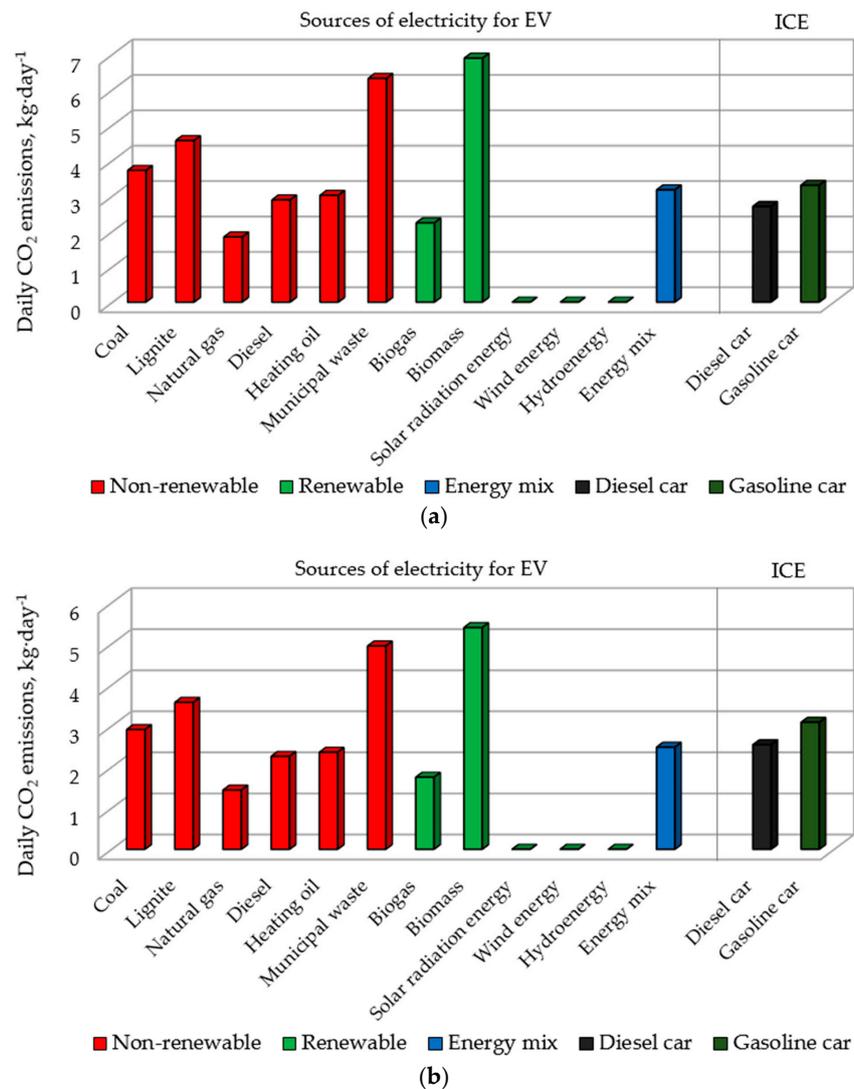


Figure 5. Cont.

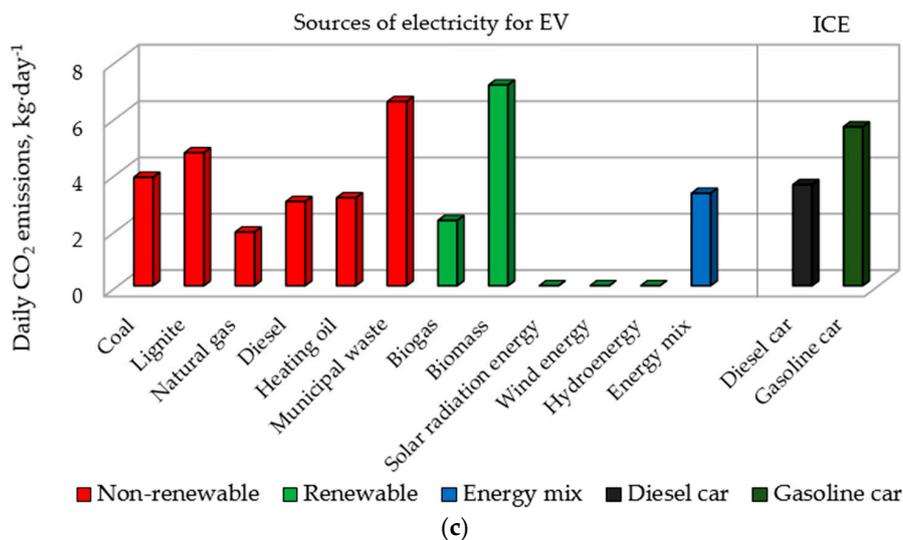


Figure 5. Comparison of daily indirect carbon dioxide emissions to the atmosphere generated by an electric car and direct emissions generated by a conventional car (distance of 26 km): (a) city, (b) sedan, (c) SUV.

Currently, the number of registered EVs in Poland is negligible compared to ICE cars. The main reasons for such a situation are higher costs, the lack of a sufficiently developed infrastructure for charging EV batteries (they are most often found only in large urban agglomerations), and limited driving range. Hence, it should be expected that the fastest development of electro mobility will take place in large cities. In order to check the potential impact of replacing part of the ICE with the EV on the daily CO₂ emission in the city with the current We_{CO_2} emission coefficient, an analysis was made based on the city of Warsaw—the capital of Poland.

The number of diesel, gasoline, and electric cars was estimated based on the Central Statistical Office [69] on transport in Poland (Table 4). Assuming the average direct emission for all ICE classes (diesel—2.95 kgCO₂·day⁻¹, gasoline—4.0 kgCO₂·day⁻¹), the average indirect emission for all EV classes (2.98 kgCO₂·day⁻¹), and the replacement of conventional cars with electric ones in the amount of 25%, 50%, and 75%, the environmental consequences for a capital city were estimated. The results are shown in Figure 6.

Table 4. Estimated number of cars, depending on the type of fuel for the city of Warsaw.

City	Voivodeship	City Population	Estimated Number of Cars		
			Diesel	Gasoline	Electric
Warszawa	Masovia	1,769,529	335,848	569,939	249

Despite the fact that in the case under consideration, replacing diesel cars with EV is worse for the environment (an increase from 3 MgCO₂·day⁻¹ to 8 MgCO₂·day⁻¹), replacing gasoline cars brings a measurable positive environmental effect. The daily CO₂ emissions, if 75% of gasoline cars were to be replaced, would be reduced by over 441 MgCO₂ (the removal of CO₂ emissions from the city). The geospatial effects of changing the place of emission should indeed be considered, but such a situation would significantly reduce low emissions, which is one of the main problems in Polish cities. In the case of Warsaw, replacing 25% of ICEs with EVs would result in the amount of over 819 MgCO₂·day⁻¹, and in the case of 50% and 75%, 1638 MgCO₂·day⁻¹ and 2457 MgCO₂·day⁻¹, respectively. Shifting emissions to the power plants located outside the cities, in addition to better control of pollutant emissions into the atmosphere (constantly monitored emission levels), also provides the of dilution of emissions in the non-urban areas. Such action allows one to maintain the permissible

level of emissions, in contrast to urban agglomerations where transport is responsible for a smog effect and overall poor air quality.

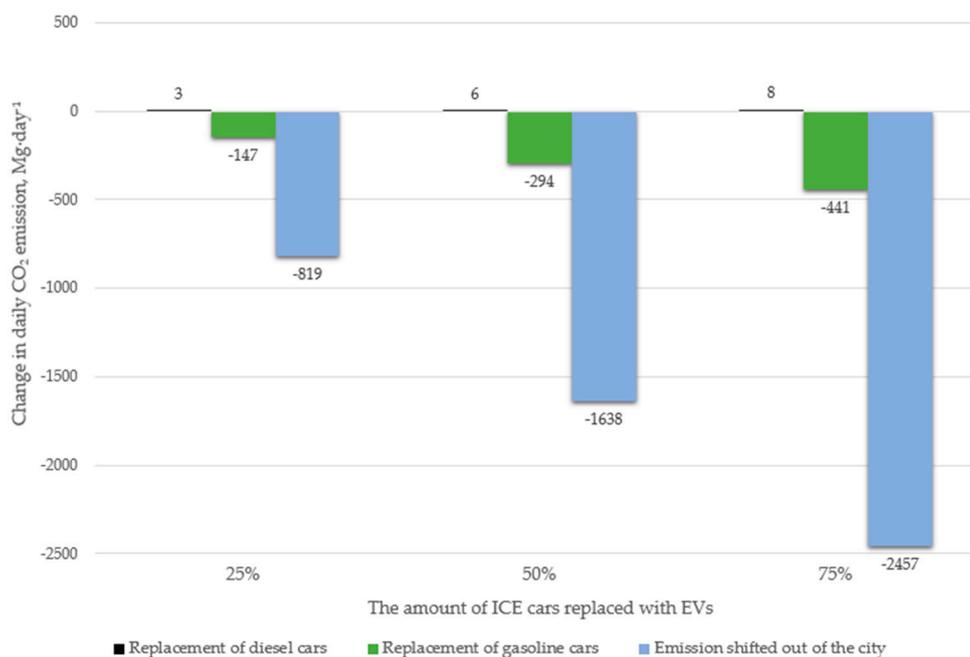


Figure 6. Change in daily CO₂ emissions as a result of replacing ICEs with EVs.

Energy Mix—Sensitivity Analysis

From an ecological point of view, it would be better to charge the batteries with energy from renewable sources—especially from the sun and wind. Such actions would allow one to achieve a significant potential for reducing air pollution in the transport sector. The gradual increase in the share of renewable energy sources in electricity production and the abandonment of coal is one of the framework points of the European Union’s low-carbon policy. It is, therefore, expected that in subsequent years, in countries with a dominant share of fossil fuels, an increase in electricity production from renewable sources will be observed. In addition, the CO₂ emission limit introduced in recent years in the European Union for newly manufactured ICEs will significantly reduce the direct emissions generated by these cars [70]. Therefore, appropriate decisions should be made in shaping the country’s energy policy to strive to minimize indirect carbon emissions, ultimately.

Indirect emissions due to the daily driving were also compared with direct emissions depending on the change in the emission value of the energy mix (Figure 7). In the presented case, it was considered how the percentage change in the emissivity indicator for the Polish energy mix will affect the environmental performance of the EV use. In the City class, for indirect emissions to be lower than direct emissions, the emission coefficient for the energy mix would have to be reduced by around 15%. Due to the gradual increase in the share of renewable sources in electricity production in Poland, it should be recognized that this result is potentially achievable over several years. In other classes this factor would not require any reduction, however indirect emissions were slightly lower than direct emissions. In the Sedan class, an increase of approximately 2% in the We_{CO_2} emission factor for the grid mix would be enough for the indirect emission to be equal to the direct diesel emission, and for this to occur in the SUV class, this factor would have to increase by approximately 10%. The slope of the equation (directional coefficient) of daily CO₂ emissions as a function of the change in the emission coefficient for energy mix for City cars (3.172) and SUVs (3.7868) turned out to be significantly higher than the slope of the equation for Sedans (2.4863). Due to the fact that air pollution in Poland most often affects urban agglomerations, a high value of the directional coefficient for City cars, which are mainly dedicated to urban and suburban driving, is desirable. In such a situation, along with the

decrease in the We_{CO_2} emission coefficient for the energy mix, the daily value of indirect emission resulting from charging the EV batteries will decrease rapidly, thanks to which the use of the EV may prove to be an effective way to reduce CO_2 .

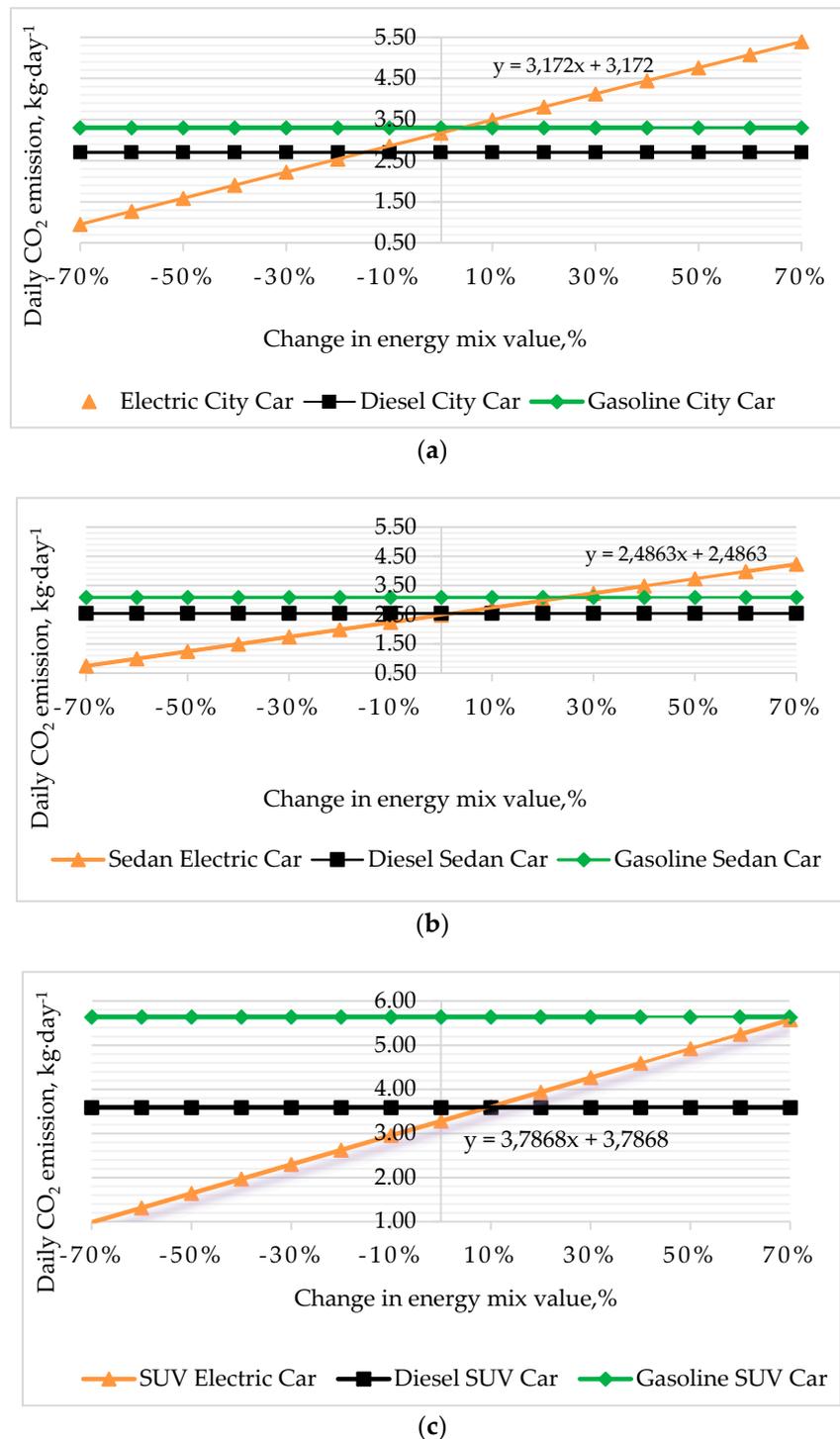


Figure 7. Comparison of direct and indirect emissions of carbon dioxide into the atmosphere when the energy mix value changes: (a) city, (b) sedan, (c) SUV.

The sensitivity analysis for the use of the EV, based on various energy sources, was also made by Ellingsen et al. [71]. The authors determined that the charging of batteries of electric vehicles of different classes, with electricity based on high carbon content fuel is 12–31% higher compared to ICEs.

Along with the decrease in the share of carbon in the production of electricity used to charge batteries, carbon dioxide emissions are gradually reduced, which coincides with the results presented. In the analyzed work, however, the emission factor for coal was slightly higher than that used for Poland's energy mix. However, for the environmental effect to be measurable, the decrease in the carbon dioxide emission factor for the energy mix would have to be much larger than 15%.

5. Conclusions

The comparison of the direct and indirect carbon dioxide emissions related only to the daily driving of the EV and different car classes with ICEs was evaluated. When comparing the direct emission of the ICE with the indirect emission of the EV, it can be seen that in countries such as Poland, with a high share of fossil fuels in electricity production, electric motors can be even more harmful to the environment than gasoline and diesel vehicles. In the case under consideration, with the current value of the We_{CO_2} emissivity factor for energy from the commercial power grid, charging EV batteries with this energy turned out to generate indirect emission, very similar to the direct emission from ICE. The worst environmental effect was recorded in the City class, where the indirect emission was $0.47 \text{ kgCO}_2 \cdot \text{day}^{-1}$ higher than the direct emission of diesel of the same class. In the remaining classes, the indirect emission was lower than the direct one, but still had a high value ($2.49\text{--}3.28 \text{ kgCO}_2 \cdot \text{day}^{-1}$). Charging electric vehicles with energy that comes from renewable sources (especially wind and sun), with zero direct emissions, and from natural gas seems to be currently the most environmentally friendly solution.

The increase in the share of renewable energy sources in electricity production will have a positive impact on the environmental performance of the EV in Poland. However, the increase in electrification in the transport sector will result in increased demand for electricity in the country. Such a situation can create problems for the domestic energy industry as well as for the stability of the power grid. It is necessary to gradually transform the energy system towards a greater share of renewable sources, which will measurably contribute to reducing the problem of air pollution. In order to limit the negative consequences of the charging of the EV batteries with energy from the power grid, in the case under consideration, the emission factor for energy from the grid should be reduced by a minimum of 15%.

The change of the ICE car into the EV for daily driving does not ensure zero emissions. In such conditions of the energy market such as in Poland it leads only to a considerable reduction of pollutant accumulation in urban areas, especially in large cities. The air quality is improved locally, and the noise level is reduced, undoubtedly improving the comfort and quality of life of their inhabitants. Unfortunately, however, the emission concentration changes only the location. To achieve a measurable reduction potential of carbon dioxide emissions into the atmosphere, electricity used to charge the EV batteries should be produced from renewable sources.

The manuscript is also a basis for future research on the environmental effects of the implementation of electric cars depending on the domestic share of individual sources in electricity production. The main limitation in the article was the exclusion from the analysis of the environmental effects of producing and recycling ICEs and EVs, as well as secondary processes such as fuels production and delivery to the petrol stations/power plant etc. Due to the fact that these activities are carried out in countries with different footprints for the environment, the scope of the manuscript could be lost and unclear (as a result). Future work should also focus on the geospatial effects of changing the place of carbon dioxide emissions due to the use of electrification of road transport as a tool to reduce carbon dioxide emissions. Another issue could be the analysis of the impact of additional factors, such as the ratio of gasoline/diesel prices to electricity, tax increase, and social status on drivers' behavior in terms of the number of daily kilometers traveled for a particular car category and type.

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Abbreviations

BEV	battery electric vehicle
EEA	European Environment Agency
EU	European Union
EV	electric vehicle
GHG	greenhouses gases
HEV	hybrid electric vehicle
ICE	internal combustion engines
PHEV	plug-in hybrid electric vehicle
REEV	range extended electric vehicle
VKT	vehicle kilometers of travel

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