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# The Development of Electromobility in Poland and EU States as a Tool for Management of $CO_2$ Emissions

**Karol Tucki [1,*], Olga Orynycz [2,*], Antoni Świć [3] and Mateusz Mitoraj-Wojtanek [1]**

[1] Department of Organization and Production Engineering, Warsaw University of Life Sciences, Nowoursynowska Street 164, 02-787 Warsaw, Poland

[2] Department of Production Management, Bialystok University of Technology, Wiejska Street 45A, 15-351 Bialystok, Poland

[3] Faculty of Mechanical Engineering, Institute of Technological Information Systems, Lublin University of Technology, Nadbystrzycka 38 D, 20-618 Lublin, Poland

* Correspondence: karol_tucki@sggw.pl (K.T.); o.orynycz@pb.edu.pl (O.O.); Tel.: +48-593-45-78 (K.T.); +48-746-98-40 (O.O.)

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**Abstract:** The article analyzes the dynamics of the development of the electromobility sector in Poland in the context of the European Union and due to the economic situation and development of the electromobility sector in the contexts of Switzerland and Norway. On the basis of obtained data, a forecast was made which foresees the most likely outlook of the electric car market in the coming years. The forecast was made using the creeping trend method, and extended up to 2030. As part of the analysis of the effect of the impact of electromobility, an original method was proposed for calculating the primary energy factor (PEF) primary energy ratio in the European Union and in its individual countries, which illustrates the conversion efficiency of primary energy into electricity and the overall efficiency of the power system. The original method was also verified, referring to the methods proposed by the Fraunhofer-Institut. On the basis of all previous actions and analyses, an assessment was made of the impact of the development of the electromobility sector on air quality in the countries studied. Carbon dioxide tank-to-wheels emission reductions which result from the conversion of the car fleet from conventional vehicles to electric motors were then calculated. In addition to reducing carbon dioxide emissions, other pollutant emissions were also calculated, such as carbon monoxide (CO), nitrogen oxides ($NO_x$) and particulate matter (PM). The increase in the demand for electricity resulting from the needs of electric vehicles was also estimated. On this basis, and also on the basis of previously calculated primary energy coefficients, the emission reduction values have been adjusted for additional emissions resulting from the generation of electricity in power plants.

**Keywords:** electromobility; $CO_2$ reduction; EU

## 1. Introduction

The continuous development of all European Union (EU) countries contributes directly to the development of the road transport sector, both passenger and freight [1–3]. The number of cars throughout Europe is increasing at a much faster pace than was would result from the increase in the number of inhabitants [4]. This affects the growth in consumption of crude oil and its derivatives, as well as the increase in the emission of air pollutants from transport [5,6].

In 2016, almost 383 million vehicles were registered in the European Union, of which over 85% were passenger cars [7]. Most EU countries, including Poland, note the growth of registered vehicles every year [8,9]. This is connected with economic development and the increase in Gross Domestic

Product (GDP) [10,11]. In addition, the number of people living in the European Union is increasing year by year [12,13].

Protection of air purity and activities related to the reduction of greenhouse gas emissions from transport are a priority in the climate and energy policies of the European Union bodies [14,15].

Many European Union countries have noticed the significant role of road transport, including the increasing number of personal forms of transport, emissions of greenhouse gases and other harmful substances into the atmosphere, which directly affects the deterioration of air quality in European cities [16,17]. Some of those cities have taken measures to develop electromobility and other alternative fuels that will enable reductions in emissions [18,19].

In recent years, the European market has seen an increase in general interest in electric vehicles [20,21] although the concept of an electric car was created a long time ago [22,23]. The pioneering country in the subject of electromobility was a non-EU European state, but a member of the European Economic Area maintaining close trade relations with it, i.e., Norway [24,25]. It was there that social incentives for using electric vehicles began to appear in the 1990s. To this day, Norway is a country that is characterized by the greatest dynamics of development among all the countries in Europe [26,27]. The situation is similar in Switzerland [28].

Poland, not unlike many other European Union countries, is attempting to fulfil commitments regarding the environment and climate contained in international agreements [29–31].

Regardless of improvements in vehicles and the automotive industry, transport still has a negative impact on air quality [32–34]. The most commonly used fuels in road transport are those with the highest emission levels: diesel and petrol [35,36]. In order to reduce the emission of air pollutants, research and development works on alternative fuels and methods of vehicle power supply have been underway for many years [37,38]. Currently, there are many different options available on the market, including electric, hydrogen cell, hybrid, partly conventionally-fueled vehicles, as well as vehicles powered by compressed natural gas (CNG) or propane-butane liquid gas (LPG) [39,40]. All of these alternative drives, as compared to conventional internal combustion engines, emit significantly less carbon dioxide and other direct air pollutants [41,42].

The introduction of electric transport is a new strategy to improve the greenhouse gas emission (GHG) balances of cities and territorial systems [43–46]. An example of an implemented program is "European Initiative on Smart Cities" which sets a target of a 40% reduction in GHG from 1990 levels by 2020. The objective can be achieved through a combination of organizational innovation, the deployment of low-carbon technologies, intelligent management of energy production and consumption. The main focus is on energy-efficient construction, local energy networks and transport efficiency.

Electromobility actually is, and will be, a great challenge equally for energy producers, transmission system operators and energy distributors [47]. Its development undoubtedly affects the operation of transmission and distribution grids [29]. The emergence of an increasing number of electric cars on the market will result in point spikes in energy consumption. Electric car batteries will be charged mainly at night. This will align the so-called night valley, which is a decrease in the demand for electricity during the night (controlled by a smart meter). Therefore, the power balancing systems in low-voltage transmission grids, as well as management of the balance difference and technical losses of electricity, will be necessary. Works are in progress on the program for discharging batteries in order to use of a car as a form of mobile energy storage that would return energy to the grid at the peak of demand. The development of national electromobility involves not only an increase of the number of electric vehicles on public roads, but also the continuous development of the charging infrastructure [48,49]. A sufficient number and availability of vehicle charging points is a key factor enabling faster distribution of these types of vehicles [50,51]. The introduction of electromobility will stimulate completely new approaches and tools for charging station management, as well as electrical energy management and power balancing systems. Also, new customer management applications, billing services and mobile navigation applications for drivers, together with seat reservation, and loyalty programs for passengers have to be developed.

Some European Union countries try to reduce the level of emissions of carbon dioxide and other air pollutants by reducing their amounts in the transport sector, through a policy that favors the development of alternative fuels [52,53]. The two most common choices among the member states are electric or LPG/CNG vehicles [54,55]. On the basis of the report on the development of electromobility in Europe, an analysis of national alternative fuel development plans was carried out and a table summarizing the activities of the European Union countries in this sector was drawn up [56].

Due to European trends, the article focuses on the development of electric vehicles in Poland and in the European Union, as well as on the impact of these changes on $CO_2$ emissions and improvement of air quality. In addition, Switzerland and Norway were also included in the analysis.

Table 1 presents the current attitude of European countries towards the development of individual drives of alternative vehicles. The table specifies whether the country possesses and implements the national development policy framework (NDPF) in a given field. The field "low ambition" means that there are documents in a given country regarding the development of alternative fuels, but those are not legal acts, specific declarations or documents binding in any way. The "no NDPF" field means that the country does not have a national development policy framework or other documents regarding alternative fuels published officially by state institutions.

**Table 1.** Attitude of European countries towards the development of individual alternative drives.

| Country | Vehicles Powered by Electricity | Vehicles Powered by LPG/CNG | Low Ambition | No NDPF |
|---|---|---|---|---|
| Austria | ● | | | |
| Belgium | ● | ● | | |
| Bulgaria | ● | | | |
| Croatia | | | ● | |
| Cyprus | | | | |
| Czech Republic | | ● | | |
| Denmark | ● | | | |
| Estonia | | | ● | |
| Finland | ● | | | |
| France | ● | | | |
| Greece | | | | ● |
| Spain | | | ● | |
| The Netherlands | ● | | | |
| Ireland | ● | | | |
| Lithuania | | | ● | |
| Luxembourg | ● | | | |
| Latvia | | | ● | |
| Malta | | | | ● |
| Germany | ● | | | |
| Poland | ● | | | |
| Portugal | ● | | | |
| Romania | | | | ● |
| Slovakia | | | ● | |
| Slovenia | | | | ● |
| Sweden | | | | ● |
| Hungary | | ● | | |
| Great Britain | ● | | | |
| Italy | | ● | | |

The ● symbol means attitude of European countries towards the development of individual alternative drives.

The analysis of the results presented in Table 1 indicates that twelve out of twenty-eight European Union partner countries (including Poland) focus mainly on the development of transport based on electric vehicles. Four of the Member States are focused on the development of LPG/CNG vehicles, six have low ambitions and five do not possess a national policy framework for the development of alternative fuels. An interesting case is Belgium, which supports the development of both electric vehicles and those powered by LPG/CNG.

The governments of many countries have realized the difficulties that electric cars may face when entering a market dominated by conventional vehicles [57–59]. Some countries have therefore decided to use incentives to convince the populace to replace their combustion vehicles with electric alternatives [60,61].

These incentives include various kinds of tax allowances, subsidies for vehicle purchases and other non-financial incentives [62,63]. However, this is a temporary measure that helps the electromobility sector to strengthen its market position [64,65]. In the later period, the scale effect is expected, which will cause a drop in market prices and a greater increase in the popularity of electric cars [66,67].

Based on the data available on the website of the European Alternative Fuels Observatory (EAFO) [68] and a report published by the European Automobile Manufacturers' Association (ACEA) [69], a list of the most important incentives and privileges for electric car owners was created (Table 2).

**Table 2.** The incentives offered for purchasing and using electric cars in the European Union, Norway and Switzerland.

| Country | Subsidies for the Purchase of a Vehicle | Road Tax Exemption | Registration Fee Exemption | Other Tax Allowances | Non-Financial Incentives |
|---|---|---|---|---|---|
| Austria | ● | ● | ● | ● | ● |
| Belgium | ●/○ | ●/○ | ●/○ | ○ | ○ |
| Bulgaria | ○ | ● | ○ | ○ | ○ |
| Croatia | ○ | ○ | ●/○ | ○ | ○ |
| Cyprus | ○ | ●/○ | ● | ○ | ○ |
| Czech Republic | ○ | ● | ○ | ○ | ○ |
| Denmark | ○ | ●/○ | ●/○ | ○ | ● |
| Estonia | ○ | ○ | ○ | ○ | ○ |
| Finland | ● | ○ | ●/○ | ○ | ○ |
| France | ● | ○ | ●/○ | ○ | ● |
| Greece | ○ | ● | ● | ● | ○ |
| Spain | ○ | ●/○ | ○ | ○ | ● |
| The Netherlands | ○ | ● | ● | ○ | ○ |
| Ireland | ● | ●/○ | ○ | ● | ● |
| Lithuania | ○ | ○ | ○ | ● | ● |
| Luxembourg | ○ | ●/○ | ● | ○ | ○ |
| Łatvia | ○ | ● | ● | ○ | ● |
| Malta | ● | ●/○ | ●/○ | ○ | ○ |
| Germany | ● | ●/○ | ○ | ○ | ● |
| Norway | ○ | ●/○ | ●/○ | ● | ● |
| Poland | ○ | ○ | ○ | ○ | ● |
| Portugal | ● | ○ | ● | ● | ● |
| Romania | ● | ● | ● | ○ | ○ |
| Slovakia | ○ | ● | ●/○ | ○ | ● |
| Slovenia | ● | ●/○ | ●/○ | ○ | ● |
| Switzerland | ○ | ●/○ | ●/○ | ● | ○ |
| Sweden | ● | ● | ○ | ○ | ● |
| Hungary | ○ | ● | ● | ○ | ● |
| Great Britain | ● | ● | ● | ○ | ● |
| Italy | ○ | ●/○ | ○ | ○ | ● |

The ● symbol means that there are incentives or privileges in the country; ●/○ marks partial occurrence of incentives, for example temporarily or only in certain regions; The ○ symbol means a complete lack of incentives.

## 2. Materials and Methods

The work was based on an analysis of official reports on the electromobility sector and the electricity power system in Europe. Other source materials available in this topic were also used for the calculations and assumptions made. On the basis of the information obtained, an analysis of the dynamics of the development of the sector in Poland and Europe was carried out.

Using the creeping trend method, a forecast was created illustrating the sector's outlook in the analyzed countries up to 2020. This method is a numerical tool for identifying the development trend of the forecast variable. So, at the input, there is an n-element time series (periods or moments) containing empirical values, and at the output, also an n-element sequence of theoretical values. In order to use the method correctly, it is necessary to perform some basic steps:

- Arbitrary determination of the value of the smoothing period l. The l parameter is the only parameter of the Hellwig method that is not estimated, but determined arbitrarily. It must be an odd, natural number and $2 < l < n$ (necessary condition);
- Estimation of k linear models of development trends, that denotes the number of linear segment models;
- Calculation of segmented theoretical values of the forecast variable;
- Calculation of the final theoretical values of the explanatory variable.

In order to accurately calculate the ecological effect of the changes taking place, an original method has been developed for calculating the primary energy factor (PEF) which reflects the efficiency of the power system of a given country in the context of conversion of primary energy into electricity. The index was also verified using methods contained in the report published by the largest organization in Europe in the field of applied research and its implementation, i.e., the Fraunhofer-Institut. These methods were proposed by a team working as part of research on the assessment of the possibility of calculating the primary energy coefficient for electricity in the context of the official update of this coefficient in EU documents. Using the data obtained from the review of reports and literature, as well as using the results of calculations and forecasts and the aforementioned indices, the ecological effect accompanying the changes was calculated. Thanks to the study of change dynamics and the forecast made, the expected impact of electromobility on air quality in the studied area was also calculated and the values of tank-to-wheels reduction (hereinafter referred to as reduction) of pollutant and greenhouse gas emissions were determined, which was the main objective of this paper.

### *2.1. Research on the Dynamics of Electromobility Development in the European Union*

On the basis of vehicle registration data in the European Union, Norway and Switzerland from the report prepared by the International Council on Clean Transport (ICCT), as well as data on the car fleet of individual European countries monitored by the European Alternative Fuels Observatory (EAFO), a chart was drawn up which presents the dynamics of the development of the electric car market in the European Union, Norway and Switzerland [63,64]. The chart starts from 2009, as in previous years no significant interest in electric cars was noted. With the exception of a few countries (including Great Britain, France, The Netherlands, Norway or Germany), no electric cars were registered in Europe before 2009. Presented below (Figure 1) is the cumulative number of electric vehicle registrations in the EU-28, Norway and Switzerland. Under the heading "EU-13 excluding Poland", there are twelve countries that joined the European Union after 2004 which have been presented in a collective manner. They are Bulgaria, Croatia, Cyprus, the Czech Republic, Estonia, Lithuania, Latvia, Malta, Romania, Slovakia, Slovenia and Hungary. The real data are marked with continuous lines in the graph, and the predicted growth is marked with dashed lines. The forecast was prepared using the creeping trend method and assumes a continuous increase in the number of new registrations in the following years.

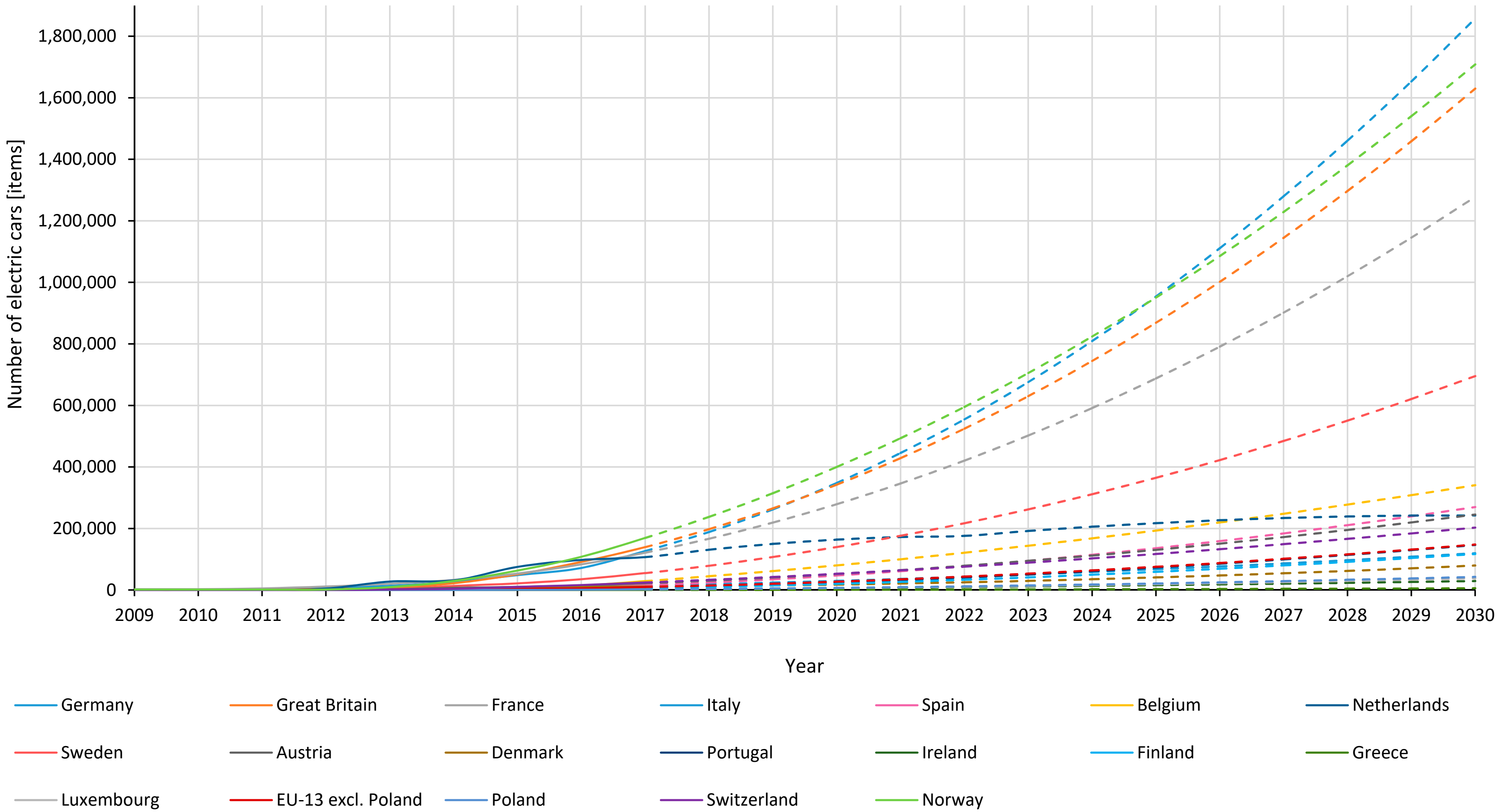


**Figure 1.** The cumulative number of new electric car registrations in the European Union, Norway and Switzerland in 2009–2017 with a forecast until 2030.

The applied method—the creeping trend method with harmonic weights—is based on historical data showing the formation of the phenomenon in the analyzed period. The data on the number of electric car registrations in Norway and Switzerland in 2009–2012 were extrapolated on the basis of actual values in the remaining years. It should be noted that the chart shows the number of cars that were registered for the first time in a given country. The graph clearly shows that there are five countries that are unambiguous sector leaders: The Netherlands, France, Germany, Great Britain and Norway. In total, the number of new registrations in these countries amounted to 211,757 units in 2017, which is over 73% of all new registrations in the analyzed area. The cumulative number of electric car registrations in the analyzed period in Poland was only 2265 (Figure 2). In 2017, 1143 vehicles were registered, which constitutes 0.40% of new registrations in the countries studied, and ranks well below the European average (15,208).

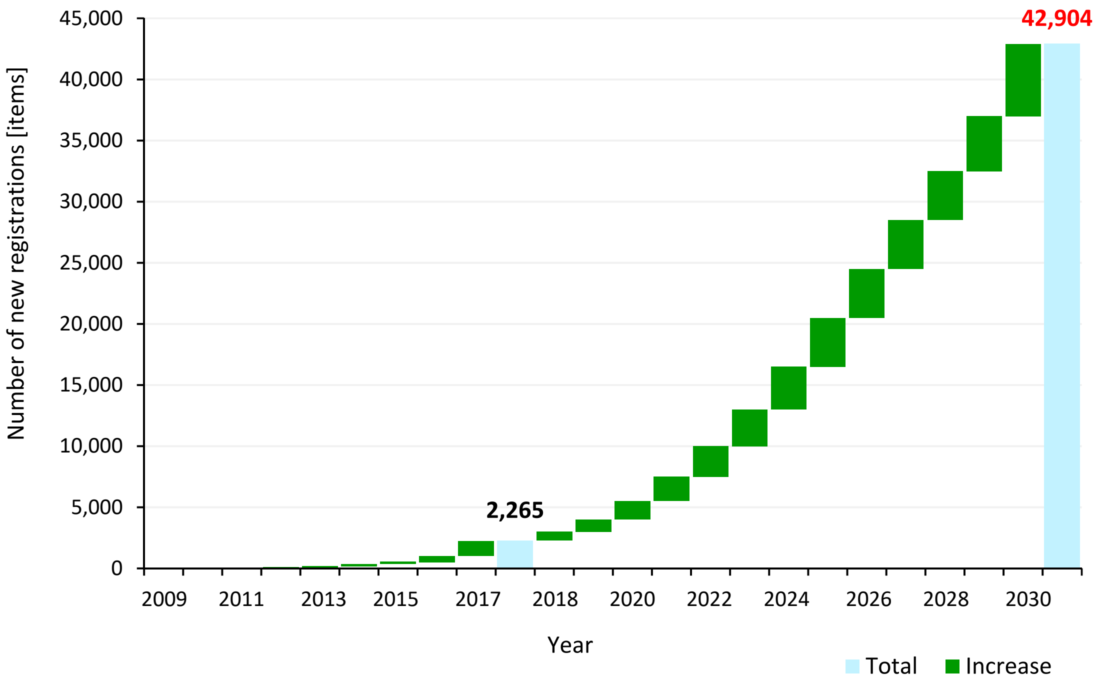


**Figure 2.** New registrations of electric cars in Poland in 2009–2017 with a forecast until 2030.

Compared to other EU countries, there are not very many electric cars registered in Poland. However, almost forty times more vehicles of this type were registered in 2017 than in 2011, which means an increase of 3841%. By comparison, in Great Britain, which is one of the European leaders in the sector, the growth in these years was 23,797%. It should be remembered that the United Kingdom, as well as other countries which are described as the European leaders of electromobility, is a highly developed country and is ranked very high in terms of economic conditions, which is the result of factors such as the pace of GDP changes, deficit reduction and decline in unemployment. When comparing the development of Polish electromobility to that of other EU-13 countries, it can be noted that the situation is completely different in this case. The cumulative number of registrations in the years 2009–2017 in Poland amounted to 2265 units, which is over 18% of all registrations that took place in 13 countries. The dynamics of changes is also greater. In 2011, only 783 electric cars were registered in all EU-13 countries, in 2017—4.155. This corresponds to a change of 431%, while, as mentioned, this value is above 3800% for Poland. The dynamics of changes is enormous and, as can be seen in the previous figure (Figure 1), in most countries, the highest increase occurred after 2013. This is probably related to the introduction in 2014 of strict EURO6 exhaust emission standards. Many manufacturers in the automotive industry noticed the need to have electric cars on offer, which contributed to the greater availability of this type of vehicle on the market.

## 2.2. Primary Energy Indicator

In order to operate electric vehicles, electricity stored in batteries is used [70,71]. The batteries are usually charged at charging points connected directly to the power grid [72]. The electricity used is known as final energy [73,74]. A particular amount of primary energy, i.e., energy contained in sources or energy carriers (e.g., in fuels combusted in a power plant), is needed for its production and delivery [75,76].

The average PEF (Primary Energy Factor) for the EU countries, mentioned in the Directives of the European Union and Council is 2.5 [77,78]. This value means that the average efficiency of the power system in the entire European Union, particularly the efficiency of electricity generation, is 40%. The indicator was designated in 2012 and has not been officially updated since then.

Due to the fact that the energy structure in Poland and Europe has changed since then, an original method for calculating the PEF indicator has been developed, and calculations for individual countries of the European Union have been made, for the purposes of the analysis [79]. The method is a simplified way of calculating the indicator and enables its determination using basic data concerning the power system. It is based mainly on the share of individual fuels in the national energy structure and takes into account the efficiency of generating electricity from various sources. It also considers the primary energy contained in individual types of fuels.

The efficiency of primary energy conversion for each type of fuel has been estimated on the basis of [80]. The final stage of calculations is the calculation of the PEF indicator, taking into account the primary energy of the carrier life cycle:

$$\mathrm{PEF}_r = \sum_{i=1}^{n} \frac{\mathrm{E}_i}{\mathrm{E}_c} \cdot \eta_i^{-1}$$

where, for the $n$ number of sources, $i$ represents:

- $\mathrm{E}_i$ is the amount of electricity produced from a given source in the year $r$ in the country,
- $\mathrm{E}_c$ is the total amount of electricity produced in the year $r$ in the country,
- $\eta_i$ is the efficiency of converting primary energy into electricity for a given fuel.

The $\mathrm{PEF}_{2016}$ indicator thus calculated for Poland is 2.34 and has a lower value than that provided in the directive. However, due to changes in electric power systems and the dynamic development of renewable energy sources in recent years, the indicator, averaged by the weighted average method, is currently also lower for the entire European Union, amounting to 2.19. Figure 3 compares the $\mathrm{PEF}_{2016}$ indicators calculated for all the EU-28 countries with its average value from 2012 and now.

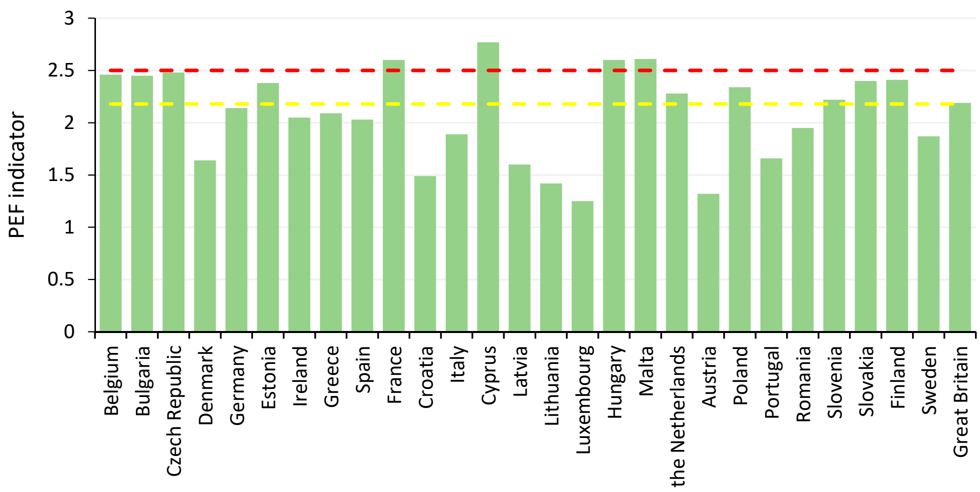


**Figure 3.** List of PEF indicators calculated for all EU-28 countries: red line—$\mathrm{PEF}_{2012}$, yellow line—$\mathrm{PEF}_{2016}$.

The lowest values of the PEF indicator occurred in Luxembourg and Austria, and, among the EU-13 countries, Lithuania and Croatia. This is due to the relatively high share of renewable energy sources (RES) in the production of electricity, and to the fairly low share of solid fuels. In the case of Luxembourg, renewable energy sources cover as much as 85% of the demand for electricity; in the case of Austria, it is nearly 79% [81].

In order to validate the correctness of the selected method, its results were compared with the values obtained using the methods proposed in the document published by the Fraunhofer-Institut [78]. The results of the index calculation are presented in the table below (Table 3).

**Table 3.** Primary PEF energy indicators in the present area of the European Union in 2001–2016—a comparison of the author's original method with the methods proposed by the Fraunhofer-Institut.

| Year | Author's Method | Method 1 | Method 2 | Method 3 | Method 4 |
|---|---|---|---|---|---|
| 2001 | 2.46 | 2.40 | 2.40 | 2.52 | 2.64 |
| 2002 | 2.45 | 2.39 | 2.39 | 2.51 | 2.63 |
| 2003 | 2.44 | 2.39 | 2.38 | 2.50 | 2.63 |
| 2004 | 2.43 | 2.38 | 2.37 | 2.50 | 2.62 |
| 2005 | 2.42 | 2.37 | 2.36 | 2.49 | 2.61 |
| 2006 | 2.41 | 2.35 | 2.32 | 2.47 | 2.59 |
| 2007 | 2.39 | 2.33 | 2.27 | 2.45 | 2.56 |
| 2008 | 2.37 | 2.31 | 2.23 | 2.43 | 2.54 |
| 2009 | 2.34 | 2.28 | 2.18 | 2.40 | 2.52 |
| 2010 | 2.31 | 2.26 | 2.14 | 2.38 | 2.49 |
| 2011 | 2.31 | 2.22 | 2.09 | 2.35 | 2.45 |
| 2012 | 2.27 | 2.19 | 2.04 | 2.31 | 2.41 |
| 2013 | 2.23 | 2.15 | 1.99 | 2.28 | 2.38 |
| 2014 | 2.21 | 2.11 | 1.94 | 2.24 | 2.34 |
| 2015 | 2.20 | 2.08 | 1.90 | 2.21 | 2.30 |
| 2016 | 2.18 | 2.04 | 1.83 | 2.17 | 2.26 |

The following calculation methods are selected for the calculation process:

- Calculation Method 1 is designed to provide a calculation method that is in line with the Eurostat primary energy calculation;
- Calculation Method 2 is designed to provide the most appropriate calculation method reflecting the total consumption of nonrenewable sources;
- Calculation Method 3 is a variation of calculation method 1 in order to analyze the impact of changing the allocation method for Combined Heat and Power (CHP) from the "International Energy Agency (IEA) method", that allocates the primary energy input to the outputs in relation to their output energies) to the "Finish method", that uses a reference system to allocate the output);
- Calculation Method 4 modifies calculation method 3 by adding the life cycle perspective to the conventional fuels.

The PEF indicator for each of the methods, both the author's and those proposed by the Fraunhofer-Institut, differs from the coefficient set out in the European Union and Council Directives: it is definitely lower. This most likely results from the more detailed approach to calculations and energy conversion used in all the five methods. In addition, the Directive does not specify when exactly the indicator was calculated, and does not show how it was calculated. According to the calculations made with the presented methods, the PEF with a value of 2.5 could be observed before 2001 (methods 1, 2 and the author's method), in 2004 (method 3) and in 2010 (method 4).

The following figure (Figure 4) shows the visualization of results using a line graph. The average value for the Fraunhofer-Institut methods is marked in dashed lines.

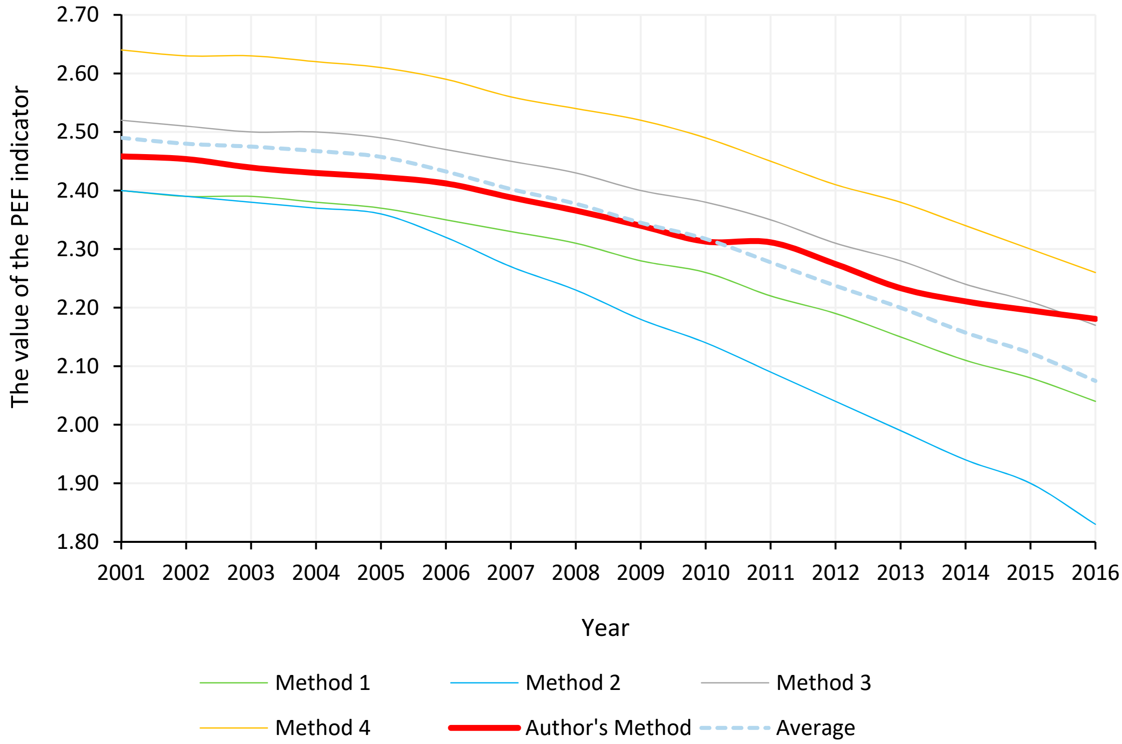


**Figure 4.** Comparison of the value of the PEF index calculated using the author's method with the values resulting from the calculations proposed by the Fraunhofer-Institut in the years 2001–2016.

As can be seen in Figure 4, the values calculated using the author method are within the range determined by the four methods proposed by the Fraunhofer-Institut**.** As part of a thorough check of the relationship between the results of the methods, a statistical verification was carried out. For four values (Methods 1, 2, 3 and 4), a standard deviation was calculated for each year; then, the difference was compared between the arithmetic mean of the methods and the calculation results. In each case, over the period of 16 years, the difference between the arithmetic average and the value of the PEF indicator calculated using the author's method was smaller than the standard deviation.

The results obtained by the author's method are the closest to those of Method 3. In this case, the relative error does not exceed 3% (its maximum value is 2.82% in 2010). The largest discrepancies occur in the case of Method 2. The error was calculated according to the formula:

$$\delta = \frac{|x_i - x_0|}{x_i}$$

where:

$\delta$. is the relative error;

$x_i$ is the value calculated using one of the Fraunhofer-Institut methods;

$x_0$ is the value calculated using the author's method.

Detailed results of the calculations are presented in the table below (Table 4).

**Table 4.** Results of statistical verification of the original calculation method of PEF primary energy factor.

| Year | PEF | $\bar{x}$ | $\sigma$ | PEF—$\bar{x}$ | $\delta_1$ | $\delta_2$ | $\delta_3$ | $\delta_4$ |
|---|---|---|---|---|---|---|---|---|
| 2001 | 2.458 | 2.490 | 0.115 | 0.032 | 2.43% | 2.43% | 2.45% | 6.88% |
| 2002 | 2.454 | 2.480 | 0.115 | 0.026 | 2.67% | 2.67% | 2.24% | 6.70% |
| 2003 | 2.439 | 2.475 | 0.117 | 0.036 | 2.06% | 2.48% | 2.44% | 7.26% |
| 2004 | 2.430 | 2.468 | 0.118 | 0.038 | 2.10% | 2.53% | 2.80% | 7.25% |
| 2005 | 2.423 | 2.458 | 0.118 | 0.034 | 2.24% | 2.67% | 2.69% | 7.16% |
| 2006 | 2.412 | 2.433 | 0.123 | 0.020 | 2.64% | 3.97% | 2.34% | 6.87% |
| 2007 | 2.388 | 2.403 | 0.129 | 0.014 | 2.50% | 5.21% | 2.52% | 6.71% |
| 2008 | 2.366 | 2.378 | 0.136 | 0.012 | 2.41% | 6.09% | 2.65% | 6.86% |
| 2009 | 2.340 | 2.345 | 0.147 | 0.005 | 2.62% | 7.33% | 2.51% | 7.15% |
| 2010 | 2.313 | 2.318 | 0.151 | 0.005 | 2.34% | 8.07% | 2.82% | 7.12% |
| 2011 | 2.312 | 2.278 | 0.156 | 0.034 | 4.12% | 10.60% | 1.64% | 5.65% |
| 2012 | 2.274 | 2.238 | 0.159 | 0.037 | 3.85% | 11.49% | 1.54% | 5.63% |
| 2013 | 2.233 | 2.200 | 0.169 | 0.033 | 3.87% | 12.22% | 2.05% | 6.17% |
| 2014 | 2.211 | 2.158 | 0.173 | 0.053 | 4.77% | 13.95% | 1.31% | 5.53% |
| 2015 | 2.195 | 2.123 | 0.174 | 0.073 | 5.54% | 15.53% | 0.67% | 4.56% |
| 2016 | 2.181 | 2.075 | 0.187 | 0.106 | 6.90% | 19.17% | 0.50% | 3.50% |

PEF—primary energy index calculated using the author's method; $\sigma$—standard deviation; $\bar{x}$—the arithmetic mean of the Fraunhofer-Institut methods; $\delta_i$—relative error for method *i*.

### *2.3. Ecological Effect and Emission Reductions*

The ecological effect of the development of electromobility in Poland and the European Union was calculated on the basis of the data presented above concerning the dynamics of electromobility development, data on vehicles and drivers' habits in a given country, as well as emissions of individual fuels. Then, the amount of emission reduction was adjusted for the emissions resulting from the increase in electricity consumption, calculated on the basis of PEF indicators.

At the beginning of the calculations, an approximate service life in a given country was estimated, based on the average age of the vehicles therein [68] and an evaluation of the economic conditions [82]. 'Service life' means the time the car is used before it is replaced with a new one. This is an important item of data from the point of view of calculating the ecological effect, in that a lot of changes regarding emission limits have been introduced in the last 30 years [83,84]. Therefore, all vehicles produced during this time differ from one another in terms of the amount of pollutants emitted [85,86]. The service life has been estimated in order to make the most accurate calculations possible.

On the basis of a report published by the Publications Office of the European Union regarding the use of vehicles by residents of the European Union as well as statistical data on the population and the number of cars in a given country, the average annual distance travelled by a passenger car in each studied country was determined [87,88]. These data were necessary to calculate the energy consumed by cars and to calculate the ecological effect. Below, Table 5 which shows the service life of vehicles and the average annual distance in the EU, Switzerland and Norway.

The last input data were specific emission levels of carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$) and particulate matter (PM) for passenger cars produced after a given year. When calculating the reduction of $CO_2$ emissions, data on average country-specific emissions were used in the studied year. Emissions of CO, $NO_x$ and particulate matter were calculated using the values included in the European emission standard for exhaust fumes; their maximum values were assumed [89–93]. Exact emission values are stated in the table below (Table 6). The average value of $CO_2$ emissions by year is stated in the table below (Table 7).

**Table 5.** The service life of the car and the average annual distance travelled by a passenger car in the EU countries, Switzerland and Norway.

| Country | Distance [km/Year] | Service Life [Years] |
|---|---|---|
| AUSTRIA | 20,091 | 13 |
| BELGIUM | 25,621 | 16 |
| DENMARK | 29,315 | 11 |
| FINLAND | 25,272 | 20 |
| FRANCE | 30,542 | 16 |
| GREECE | 21,433 | 35 |
| SPAIN | 18,470 | 30 |
| THE NETHERLANDS | 21,891 | 16 |
| IRELAND | 28,703 | 13 |
| LUXEMBOURG | 22,817 | 9 |
| GERMANY | 24,045 | 14 |
| NORWAY | 26,398 | 8 |
| POLAND | 18,788 | 31 |
| PORTUGAL | 23,966 | 35 |
| SWITZERLAND | 25,078 | 10 |
| SWEDEN | 29,416 | 13 |
| GREAT BRITAIN | 27,031 | 12 |
| ITALY | 19,354 | 27 |
| EU-13 EXCL. POLAND | 22,660 | 27 |

**Table 6.** Limits for exhaust emissions of new vehicles sold in the European Union and EEA member states. Values used in the calculations.

| Emission | Engine Type | EURO I 1993–1996 | EURO II 1997–2001 | EURO III 2002–2005 | EURO IV 2006–2010 | EURO V 2011–2014 | EURO VI > 2015 |
|---|---|---|---|---|---|---|---|
| CO [g/km] | Petrol | 2.72 | 2.20 | 2.30 | 1.00 | 1.00 | 1.00 |
| | Diesel | 2.72 | 1.00 | 0.64 | 0.50 | 0.50 | 0.50 |
| $NO_x$ [g/km] | Petrol | - | - | 0.15 | 0.08 | 0.06 | 0.06 |
| | Diesel | - | - | 0.50 | 0.25 | 0.18 | 0.08 |
| PM [g/km] | Petrol | - | - | - | - | 0.005 | 0.005 |
| | Diesel | 0.14 | 0.08 | 0.05 | 0.025 | 0.005 | 0.005 |

**Table 7.** Average $CO_2$ emissions in European Union, Norway and Switzerland in years 1993–2022 [g/km].

| Average $CO_2$ Emissions by Year [g/km] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **1993** | **1994** | **1995** | **1996** | **1997** | **1998** | **1999** | **2000** | **2001** | **2002** |
| 195 | 192 | 188 | 184 | 181 | 177 | 174 | 170 | 169 | 167 |
| **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** | **2012** |
| 166 | 163 | 162 | 161 | 159 | 171 | 147 | 143 | 138 | 133 |
| **2013** | **2014** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** |
| 127 | 123 | 120 | 118 | 118 | 118 | 117 | 117 | 117 | 117 |

Using all of the above data, and taking into account the percentage distribution of diesel and gasoline vehicles as well as the average $CO_2$ emissions data for a car in a given country, reductions in $CO_2$, CO and $NO_x$ emissions were calculated. The calculations included the manufacture year, and therefore, also the emissivity of the car replaced by an electric vehicle. This was estimated on the basis of the service life of the vehicle peculiar to the country. The results of the calculations for Poland are shown in the diagrams below (Figures 5 and 6).

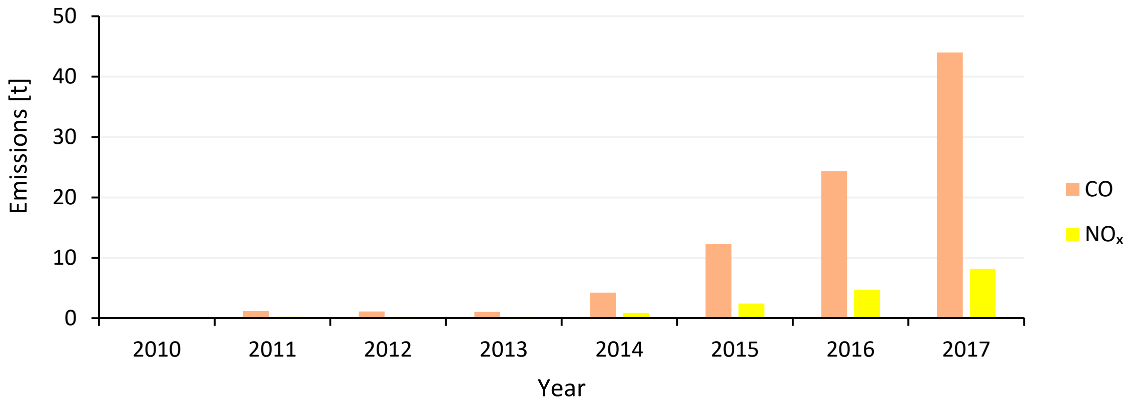


**Figure 5.** Reduction of CO and $NO_x$ emissions thanks to the replacement combustion with electric cars in Poland in 2010–2017.

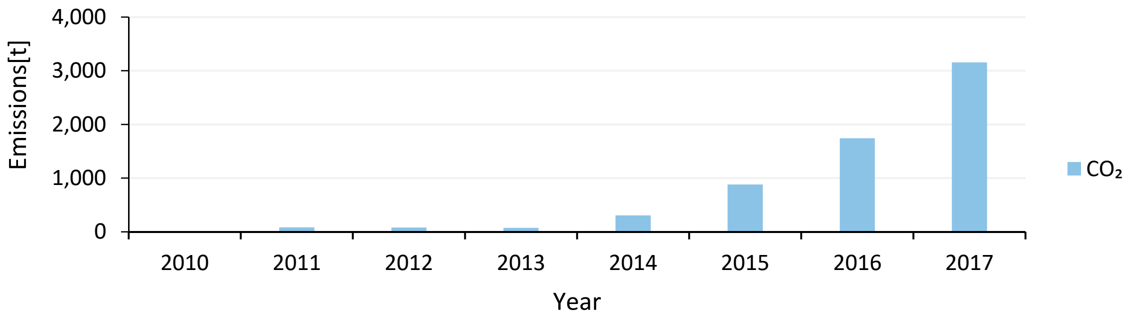


**Figure 6.** Reduction of $CO_2$ emissions due to the replacement of combustion with electric cars in Poland in 2010–2017.

The replacement of part of the car fleet from conventional vehicles to electric vehicles makes it possible to avoid the emission of a large amounts of pollution. The conversion also had a positive impact on the quality of air in cities, thanks to the avoidance of particle emissions, as shown in the graph below (Figure 7).

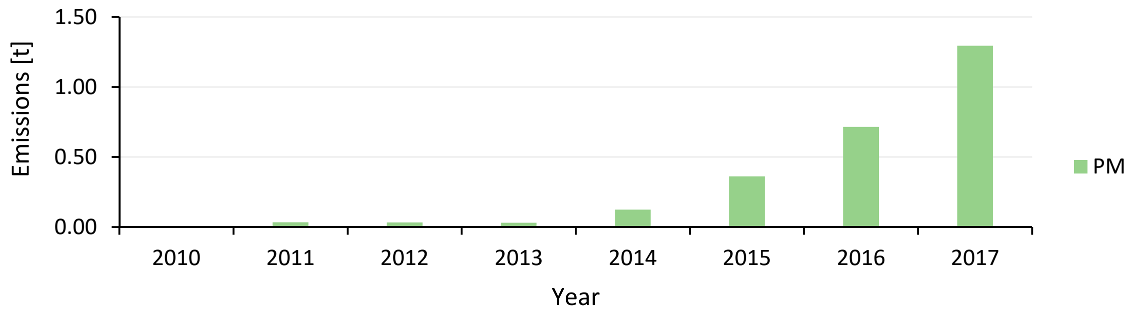


**Figure 7.** Reduction of PM emissions thanks to the replacement of electric cars in Poland in 2010–2017.

In 2017 in Poland, thanks to the replacement of cars with electric ones, emissions of over 3155 tons of carbon dioxide, over 44 tons of carbon monoxide, over 8 tons of nitrogen oxides and almost 1.3 tons of particulate matter were avoided [94]. During the entire studied period, emissions of over 6324 tons of $CO_2$, over 88 tons of CO, almost 17 tons of $NO_x$ and 3 tons of PM were avoided. The ecological effect is even greater in the countries where the increase in the number of electric cars was higher in the analyzed years [95,96]. For example, among the EU leaders in the sector, i.e., Germany (DE), Great Britain (GB) and France (F), the amount of emission reduction in individual years was as described in the table below (Table 8).

**Table 8.** Reductions in $CO_2$, CO, $NO_x$ and PM emissions thanks to the replacement with electric cars in Germany, Great Britain and France in 2010–2017.

| Emissions | Country | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|---|---|
| $CO_2$ [t] | DE | 1261 | 9741 | 16,129 | 32,178 | 52,873 | 97,692 | 101,817 | 235,793 |
| | GB | 956 | 5490 | 8666 | 17,081 | 69,595 | 134,716 | 186,487 | 220,328 |
| | F | 1238 | 15,003 | 34,168 | 51,771 | 70,208 | 117,487 | 167,675 | 212,104 |
| CO [t] | DE | 18.6 | 144.0 | 238.4 | 475.7 | 781.6 | 1444.2 | 1505.1 | 3485.6 |
| | GB | 8.9 | 49.0 | 77.4 | 153.6 | 624.1 | 1223.4 | 1689.0 | 2080.9 |
| | F | 17.5 | 212.5 | 484.0 | 733.4 | 994.6 | 1664.4 | 2375.4 | 3004.8 |
| $NO_x$ [t] | DE | 4.0 | 33.5 | 56.2 | 112.1 | 184.3 | 340.6 | 347.6 | 745.9 |
| | GB | 3.4 | 20.5 | 32.4 | 63.2 | 258.5 | 491.4 | 682.9 | 757.1 |
| | F | 5.2 | 63.4 | 146.3 | 209.7 | 276.1 | 436.3 | 592.8 | 713.2 |
| PM [t] | DE | 0.6 | 4.2 | 7.0 | 14.0 | 23.0 | 42.5 | 44.3 | 102.5 |
| | GB | 0.2 | 1.2 | 2.0 | 3.9 | 15.7 | 30.4 | 42.1 | 49.8 |
| | F | 0.5 | 6.3 | 14.2 | 21.6 | 29.3 | 49.0 | 80.0 | 88.4 |

### *2.4. Ecological Effect and Emission Reductions—Corrected Values*

The values presented above relate to the reduction of emissions of air pollutants fumed during the operation of the vehicle. Reducing their emissions will directly affect air quality, mainly in cities [97,98]. This can decrease occurrences of smog and improve air quality [99,100]. However, electric vehicles, although they hardly emit any harmful substances while driving, use electricity [101,102]. Electricity is generated in power plants and, depending on the state of the power system and energy mix in a given country, its production causes emissions of various substances into the atmosphere [103–105]. In connection with the above facts, the ecological effect of the fleet's replacement with electric vehicles was also calculated including emissions resulting from the generation of electricity.

A correction of the calculated values was made on the basis of previously estimated primary energy indicators (PEF). It allows for the determination of the primary energy from different types of media needed to power an electric vehicle.

On the basis of data on the average annual mileage of a vehicle in a given country, as well as the assumed energy consumption of an electric car in road conditions, annual electricity consumption was calculated [106,107]. Then, using PEF indicators, primary energy consumption was estimated. Based on the energy mix peculiar to a given country and the average emission values characteristic for all types of fuels (solid, gas, liquid and waste), additional emissions were determined, which accompany the operation of electric vehicles. Finally, the previously calculated emission reduction values were corrected for additional emissions related to the generation of electricity. A comparison of the cumulative primary values with those corrected, on the example of Poland in the years 2010–2017, is shown in the following graph (Figure 8). The graph also presents the $CO_2$ emission reduction values forecast on the basis of the expected number of electric cars by 2030.

The corrected reduction of $CO_2$ emissions caused by the replacement of a proportion of conventional vehicles with electric ones in Poland amounted to almost 2000 tons by 2017. In the coming years, while maintaining the growing trend for new electric cars at the assumed level, the cumulative reduction of emissions may reach 14.7 thousand tons by 2030.

Figure 9 presents a comparison of cumulative emission reductions for the European Union countries in the years 2010–2017 along with the forecast by 2030 (lighter colors). The graph shows that the largest reductions are in those countries that are leaders of electromobility (in terms of the number of registered vehicles), i.e., Great Britain, Germany and France. Poland ranks in the penultimate place before Greece (EU-13 countries excluding Poland was presented as one cumulative value).

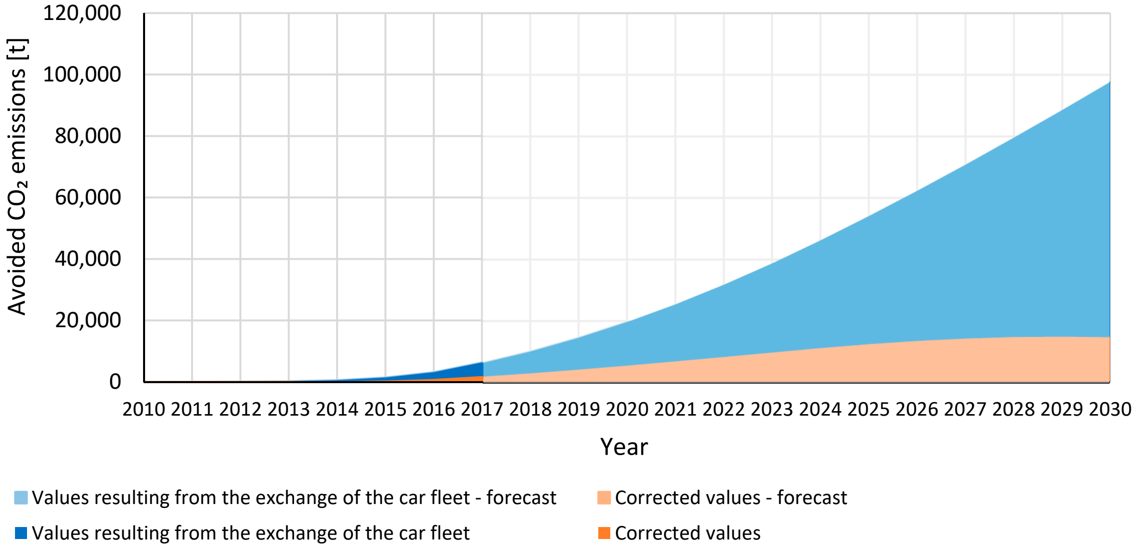


**Figure 8.** Summary of the cumulative reduction of $CO_2$ emissions resulting from the replacement of internal combustion with electrical vehicles, including values corrected in 2010–2017 with a forecast by 2030.

Throughout the European Union in 2010–2017, $CO_2$ reductions caused by the replacement of a proportion of conventional vehicles with electric ones totaled over 2.03 million tons. By 2030, the projected cumulative value is over 15.22 million tons since 2010. In 2030 alone, a reduction of 1.03 million tons of $CO_2$ is expected.

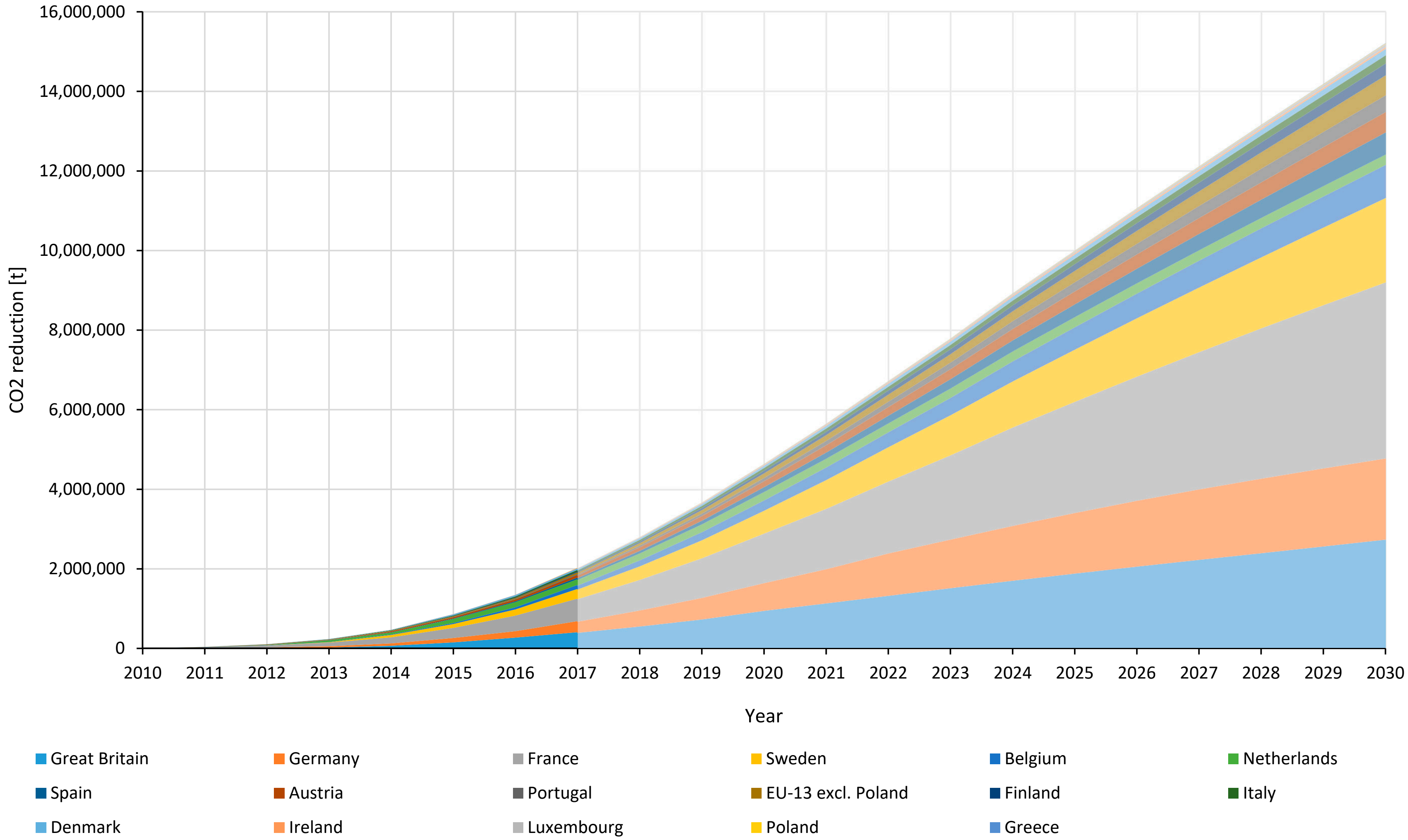


**Figure 9.** Comparison of cumulative emission reductions (after correction) for the European Union countries in the years 2010–2017 together with the forecast by 2030.

## 3. Conclusions

Although electric cars are not a very new technology, the electromobility sector in the context of private transport is still new on the market. This results in relatively high prices of this type of vehicle as compared to conventional cars. The low popularity of electric cars translates into high purchase costs which are closely related to research and development costs incurred by manufacturers, the costs of introducing new models to the market, or the production of high-performance batteries.

Based on the analysis, it can be concluded that:

- The population in the European Union, Norway and Switzerland, increased by 5.93% from 2000 to 2016, while, in the same period, the number of cars increased by 26.21%. This fact is related to the change in the automotive coefficient, which amounted to 436 in 2000 in the analyzed area, and as many as 518 in 2016. Based on the forecast of a further increase in the population and cars to be produced, it was determined that the value of the coefficient in 2021 will be 537, using the creeping trend method.
- Poland and Greece have the largest increases in the coefficient. In these countries, the value of the ratio changed from 261 to 571 and from 297 to 475 respectively. Countries such as Switzerland or Germany are characterized by a relatively small increases in the coefficient. For comparison, the average annual growth rate of the ratio in these countries is 0.56% and 0.25% respectively, and in Poland it is 4.66%.
- The analysis of electric car registrations in the studied countries showed that a total of 868,320 electric cars appeared in the European Union, Norway and Switzerland from 2009 to 2017. Norway, Great Britain, Germany and France are the undisputed leaders in the sector. In these four countries, 557,244 electric cars appeared in the analyzed period, which constitutes almost 65% of all electric cars registered in the EU, Norway and Switzerland in that period. At the same time, only 7317 electric cars were registered in Poland.
- Based on the forecast made, using the crawling trend method, it is anticipated that 9,200,449 electric cars will have been registered in the European Union, Norway and Switzerland by 2030.
- The paper proposes an original author's method for calculating the primary energy index, which was then validated based on the methods proposed by the Fraunhofer-Institut. The validation was carried out on the basis of a comparison of the 4 proposed methods with the author's method. The difference between the arithmetic mean of the methods and the results of calculations made using the author's method for 2001–2016 was smaller than the standard deviation of the methods.
- Based on the author's method, the index was calculated, which, in the case of Poland, was 2.34, and 2.19 for the European Union for the year 2016.
- On the basis of the analyses carried out, the ecological effect of replacing the conventional car fleet with the electric one was calculated. The total emission reduction in Poland until 2017 was 6325 tons $CO_2$, 88 tons CO, 17 tons $NO_x$ and 3 tons PM. Across the European Union, the emission reduction amounted to: 2,792,746 tons of $CO_2$, 27,416 tons of CO, 7346 tons of $NO_x$ and 564 tons of PM.
- Upon taking into account the increase in electric energy demand for electric cars, the reduction of $CO_2$ emissions amounted to 1935 tons for Poland and 2,031,079 tons $CO_2$ for the entire European Union by 2017.
- From the emission reductions forecast, resulting from the forecasted increase in the number of electric cars, it appears that emissions of 15,219,838 tons of $CO_2$ will be avoided in Europe by 2030, counting from 2009.
- The development of electromobility implies new approaches and the need to create new solutions in the field of energy management and vehicle operation management.

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M.M.-W. and A.Ś.; Writing—original draft preparation, K.T. and O.O.; Writing—review and editing, K.T., M.M.-W. and O.O.; Visualization, M.M.-W., K.T. and A.Ś.; Supervision, A.Ś.; funding acquisition, A.Ś.

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