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Energy and environmental implications of electromobility implementation in Poland

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Abstract. Number of fully electric cars on the roads worldwide is rapidly growing. Decreasing costs of manufacturing of Lithium-ion batteries together with strong ecology-based marketing may result in one third of electric cars in total number of passenger vehicles by 2040. Polish power industry and electricity grid must be ready to accommodate increasing and significant number of passenger electric cars. In Polish energy mix, which is dominated by coal, the ecological benefit from "green traffic" would be reduced, however not insignificant, but the main problem seems to be the preparation of the electricity grid for heavily increased demand for power. The paper presents analysis of the results of replacement petrol combustion cars with fully electrical on the basis of a range of ten modern examples of vehicles being offered on the market. Their effective ranges and power consumption have been used for prognosis for Polish electromobility and power industry. Equivalent CO_2 emissions have been calculated for electric and combustion engine vehicles, as well as increasing power demand for their charging and amounts of coal which will be necessary to cover the increase power demands in electricity grid.

1. Introduction

The share of electric cars in the total volume of new car sales in the world is growing rapidly. This also applies to Poland, where regardless of the political and economic conditions that may support or slow down this process, the number of electric vehicles traveling on the road will increase, generally following the global trends. According to Bloomberg New Energy Finance [1], by 2040, 35% of annual passenger cars sold will be electric units (EV), and the number of these cars in the world will exceed 400 million units in relation to approximately 2 billion of their total number, figure 1.

Factors that so far hampered the development of electromobility were primarily the small range of these cars and their high prices, which factors, in particular in less prosperous countries, crossed the economic rationality of such a purchase for the average car user. At the moment, on the Polish market, the net prices of electric cars start at around one hundred thousand PLN (24000 EUR) and allow to purchase a car belonging to the A segment, i.e. the smallest urban type car. In turn, in the case of a car with slightly greater functionality and performance of the C or D segment (cars of the compact and medium class), prices start at over 150000 PLN (36000 EUR). Such large prices may give rise to reasonable concerns whether during the life of such a car the buyer is able to get a refund of the additional cost (compared to the vehicle with an internal combustion engine) for using a cheaper source of energy, not to mention the profit from such an investment .

It is easy to calculate that with a moderate usage, 1000 km per month using a car with an average engine capacity (1.6L), the annual cost of fuel along with the annual change of engine oil would be around 44000 PLN (10500 EUR) after a ten-year period of use. In turn, intensive use of electric cars is undoubtedly going to be difficult for a long time due to the availability of charging points and the time that the user would have to spend during the day to replenish the energy in the car battery.

The expected increase in the sales of electric cars, in the initial stage of which we are already at the moment, results mainly from the rapidly falling prices of lithium-ion batteries and the scale effect of both electric car manufacturers and batteries for them. For example, in 2020 it was planned to start selling a new E-Golf model at a price comparable to its combustion version, while the 2017 model is priced in Poland for over 160000 PLN (38000 EUR) and the prices of the cheapest combustion versions start from less than 68000 PLN (16000 EUR) [2].

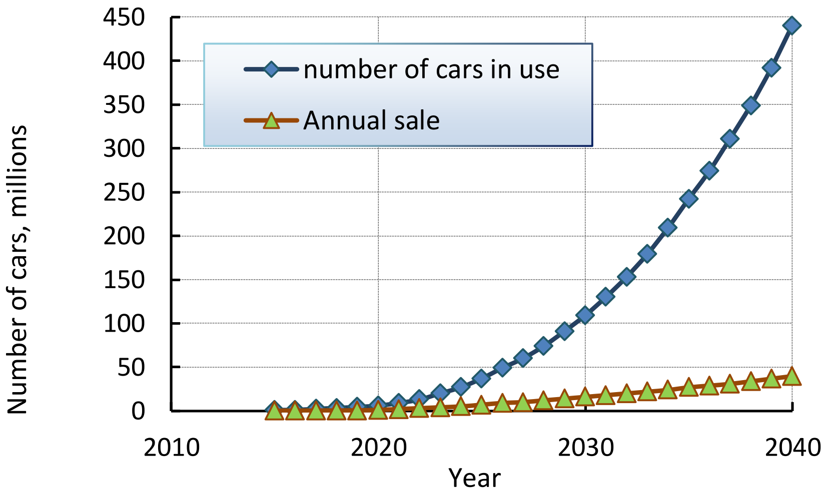

Figure 1. Sales forecast and the number of electric cars in the world according to [1].

A significant drop in the prices of electric cars may encourage, above all, users who use the car for everyday commuting and moving around the place of residence

According to data from the Central Register of Vehicles and Drivers, assuming that only vehicles with a current AC policy are involved in road traffic, there are slightly over 14,58 million passenger cars on Polish roads [3]. For the sake of accuracy, the total number of registered passenger cars exceeds slightly 22 million units, but it is difficult to find in the owners of uninsured vehicles potential buyers for electric cars.

From January to September 2018, 403343 new passenger cars and 5311 passenger and cargo cars were registered in Poland, for which group of vehicles also more and more proposals for electric cars are present. For comparison, only 428 fully electric vehicles were registered in the same period. With this residual number of electric cars sold, Poland is taking its last but one place in Europe (ahead of Greece).

Nevertheless, it is worth noting that it is an increase by as much as 42% compared to the previous year [4]. The inevitable rapid growth of electromobility will have serious implications in various areas of the economy, in particular they will affect the fuel and energy markets and energy industries. Electric cars are also seen, among others, as a remedy for smog and the greenhouse effect. In the further part of the article, predictions concerning selected aspects of the mass presence of electric cars in Poland will be presented.

2. Coal emission from electric car

Electricity belongs to secondary energy sources and the energy consumption of an electric car strictly reflects the energetic mix of electricity production in a country. Carbonization of Polish electricity grid is relatively high, so the coal trace of an electrical usage will be proportional.

According to the National Center for Emissions Management and Balancing, the CO_2 emission factor for the production of electricity from combustion sources included in the EU ETS is 781 kg CO_2/MWh [5]. This parameter applies to electricity including combustion sources, wind and water power plants, biofuels and biomass combustion, also including losses related to energy supply to the final user (electricity grid losses). The basic data characterizing the electricity production in Poland in terms of quantity and sources of origin are presented in table 1.

Table 1. Capacity installed and electricity produced accordingly to sources (state on 31.12.2017) [5].

Energy source	Capacity installed [MW]	Annual production [GWh]
Total	43 612,0	170 335
Heat power plant from which	32 233,0	140 259
- lignite	9 286,9	52 281
- hard coal	20 989,5	79 265
- gas	1 236,4	6 161
-biomass/biogas	720,2	2 552
Hydro power	2 306,0	2 719
- from which pumped storage plants	1 413,0	474
Professional wind power plants	1 374,7	3 485
Industrial heat-power plants	2 751,0	11 417
Independent RES power plants	4 947,2	12 454

The data presented above show that electricity generated by professional power industry and industrial combined heat and power plants comes to around 82.8% from coal combustion (lignite and hard coal) with the assumption that industrial combined heat and power plants are based on non-carbon sources in the same proportion as commercial power plants. In terms of installed capacity, about 74.1% are coal-fired generation units. Both in terms of produced energy and installed power, just over 52% of electricity comes from hard coal.

The real energy consumption of electric cars was estimated on the basis of a test conducted in the summer of 2018 by the Spanish portal Coches.net, the results of which were presented by Auto Świat magazine [6]. Selected car parameters and test results are presented in table 2. The test involved 10 models of electric cars, including six models sold officially in Poland, for which prices valid in September 2018 are given in PLN.

Table 2. Characteristics of cars participating in the test [6].

Car model	Battery capacity [kWh]	Charging time [hours		Range NEDC [km]	Range WLTP [km]	Net price
		2,2 kW	3-phase			
Nissan Leaf	40	19,5	7	378	285	153 800 PLN
Renault ZOE 40	41	19	6	400	300	143 500 PLN
Opel Ampera-E	60	26	5	520	380	42 990 EUR
Tesla model X	100	48	15	565	430	109 000 EUR
Tesla model S	100	48	15	632	461	109 000 EUR
Jaguar I-Pace	90	43,5	13,5	n.d.	480	354 900 PLN
Kia Soul El.	30	15,3	5,5	250	185	33 550 PLN
Hyundai Ioniq El.	30,5	14,3	5	280	204	157 500 PLN
VW E-Golf	35,8	16,5	5,25	300	219	164 890 PLN
BMW i3	33,2	14	3	300	225	165 000 PLN

From the point of view of the load on the electricity grid, the power of batteries charging is important. Table 2 shows the times of full charging using standard 2,2 kW single-phase power chargers and three-phase chargers of 6,6 kW (Kia Soul Electric, Hyundai Ioniq, Nissan Leaf), 7,2 kW (VW E-Golf), and 7,4 kW power (Renault Zoe 40, Opel Ampera-E, Tesla model X, Tesla model S, and Jaguar I-Pace). The range of cars declared by manufacturers is defined in the latest WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure). This is a global harmonized test procedure for determining fuel consumption and CO_2 emissions. With regards to electric cars, the WLTP range is much better reflecting the real conditions of use of cars than the previously reported range of NEDC test (New European Driving Cycle), whose results in the opinion of car users are generally considered misleading and overly optimistic.

Table 3 presents the results of tests of the range of selected cars. Among the car models tested, the actual energy consumption per 100 km travel distance was from 12,2 kWh to 27,5 kWh, while in the middle class cars from 12,2 kWh to 16,3 kWh and only luxury cars have an energy consumption above 20 kWh per 100 km. Then, for individual cars tested, the CO_2 emission values resulting from the emission factor applicable for Poland were determined. In Polish conditions, with a strong dominance of coal in electric production, the operation of the electric cars is associated with emissions from about 11,4 kg to 21,5 kg of CO_2 per 100 km. Assuming arithmetical average equivalent emission value of round 13,6 kg of CO_2 per 100 km and CO_2 emission of 2,136 kg from combustion of one kg of hard coal, one can say that the fuel consumption of an average electrical car on Polish roads could be estimated as 6,5 kg of hard coal per 100 km.

Table 3. Range and actual energy consumption achieved by cars in the test [6] and CO_2 emissions under the conditions of the Polish energy mix.

Car model	Actual range [km]	Actual/ WLTP range ratio[%]	Actual power consumption [kWh/100 km]	CO_2 emission [kg/100 km]
Nissan Leaf	227	79,6	16,3	12,733
Renault ZOE 40	284	94,7	14,6	11,403
Opel Ampera-E	377	99,2	16,1	12,574
Tesla model X	400	93,0	23,4	18,275
Tesla model S	422	91,5	20,6	16,089
Jaguar I-Pace	313	65,0	27,5	21,477
Kia Soul El.	218	117,8	13,6	10,622
Hyundai Ioniq El.	211	103,4	12,2	9,528
VW E-Golf	231	105,5	14,8	11,559
BMW i3	231	102,7	14,8	11,559

3. Comparison of the carbon trace between electric and internal combustion cars

With a large share of energy obtained from fossil fuels in the production of electricity as a source of power for electric cars, it is interesting to compare how much CO_2 emissions resulting from the use of electricity is less than the emissions accompanying the operation of cars with internal combustion engines. Making such a comparison requires determining the capacity of the engines, which would be adequate for cars of the size and class of those that participated in the quoted test and what would be the average fuel consumption for them.

Only petrol engines with a capacity and rated power of 1,4 dm^3/80 HP for the smallest of cars considered were accepted, i.e. for Renault ZOE 40, 1,6 dm^3/100 HP for medium-size cars, i.e. Nissan Leaf, Opel Ampera -W, Kia Soul Electric and VW E-Golf as well as 2,0 dm^3/150 HP for Tesla model X, Hyundai Ioniq Electric and BMW i3. It was assumed that the largest cars in the studied group, i.e. Tesla model S and Jaguar I-Pace, would be powered by units with a capacity of 2,5 dm^3 and 200 HP.

The most controversial are the assumptions regarding the petrol combustion per 100 km, which is a subject of huge variability influenced by numerous variables and differs between cars of different brands equipped with engines of similar capacity, depending on the type of engine, driving cycle, weight of the car or driving style.

For the purpose of this comparison, relatively low rates of combustion have been assumed, corresponding to the rather conservative, economical way of driving, taking into account that the potential buyer of an electric car is a customer paying attention to the economics of driving.

The following fuel consumption was assumed as the reference value, taking into account that the test drive was carried out in urban conditions: 7 dm^3/100 km for the engine 1,4 dm^3/80 HP, 8 dm^3/100 km for the engine 1,6 dm^3/100 HP, 9 dm^3/100 km for the engine 2,0 dm^3/150 HP, and 10 dm^3/100 km for the engine 2,5 dm^3/200 HP. Estimated CO_2 emissions for the hypothetical petrol fueled driving of cars participating in the test [7] are summarized in table 4. It was assumed that the combustion of 1 dm^3 of petrol is accompanied by the emission of 2,33 kg of CO_2 [8].

Table 4. Comparison of CO_2 emissions resulting from the use of electricity and an estimated alternative amount of petrol combustion.

Car model	Alternative combustion engine	Petrol consumption [dm^3/100 km]	CO_2 emission kg/100 km	CO_2 emission from electric car as percent of petrol emission [%]
Nissan Leaf	1,6/100 HP	8	18,64	68,30
Renault ZOE 40	1,4/60 HP	7	16,31	69,91
Opel Ampera-E	1,6/100 HP	8	18,64	67,46
Tesla model X	2,0/150 HP	9	20,97	87,15
Tesla model S	2,5/200 HP	10	23,3	69,05
Jaguar I-Pace	2,5/200 HP	10	23,3	92,18
Kia Soul El.	1,6/100 HP	8	18,64	56,98
Hyundai Ioniq El.	2,0/150 HP	9	20,97	45,44
VW E-Golf	1,6/100 HP	8	18,64	62,01
BMW i3	2,0/150 HP	9	20,97	55,12

Calculations indicate that selected electric cars emit from about 45,4% to 92,2% of CO_2 in relation to their combustion (petrol) counterparts. After rejection of the two extreme results, it turns out that statistically, the electric car emits round 67% of CO_2 of its combustion counterpart. Replacing passenger combustion engine cars with electric vehicles therefore does not introduce a revolutionary decrease in CO_2 emissions to the atmosphere, reducing it in practice by about 1/3 considering a single car.

When comparing the environmental impact of electric cars and petrol powered vehicles, one should also pay attention to the emission of greenhouse gases to the environment at the car production stage. According to [7], the manufacturing of an average electric car is associated with the emission of greenhouse gases, which in CO_2 equivalent charges every kilometer covered during the lifetime of the car with a mass of 7 kg per 100 km. At the same time, the production of a car with a gasoline engine is accompanied by greenhouse gas emissions corresponding to a mass of 4 kg per each 100 km of the car's lifetime mileage. A significant difference in the burden of car use with the share of CO_2 emissions due to the manufacturing of an electric car and combustion engine car results from a significant environmental impact caused by the production of car batteries and longer life of cars with internal combustion engines.

It is also worth adding that the process of obtaining petrol from crude oil is also not neutral for the environment and according to [8], the production of 1 liter of petrol is associated with the emission of 0,46 kg of CO_2 equivalent to the atmosphere. After taking into account these factors, a more complete

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picture of the CO_2 emissions to the atmosphere related to the operation of electric and combustion engine cars is obtained, table 5.

Since in determining the CO_2 emission related to the production of electric energy for an electric car, the electricity emission index for final consumers was used, the determined CO_2 emission figures include losses of energy distribution in the network, share of coal in electricity production and efficiency of power boilers. On the other hand, energy necessary to obtain and transport of crude oil and hard coal was not included into considerations. Such estimations would be characterized by ever more general generality and arbitrariness.

Table 5. Comparison of CO_2 emissions resulting from the use of electricity and an estimated alternative value of petrol combustion after taking into account emissions related to car manufacturing and fuel processing [kg CO_2/100 km].

Car model	Electric drive without manufacturing	Electric drive and manufacturing	Combustion drive without manufacturing	Combustion drive with manufacturing and fuel processing	Final electric/fuel car emission ratio [%]
Nissan Leaf	12,73	19,73	18,64	26,32	74,96
Renault ZOE 40	11,40	18,40	16,31	23,53	78,21
Opel Ampera-E	12,57	19,57	18,64	26,32	74,37
Tesla model X	18,28	25,28	20,97	29,11	86,83
Tesla model S	16,09	23,09	23,3	31,9	72,38
Jaguar I-Pace	21,48	28,48	23,3	31,9	89,27
Kia Soul El.	10,62	17,62	18,64	26,32	66,95
Hyundai Ioniq El.	9,53	16,53	20,97	29,11	56,78
VW E-Golf	11,56	18,56	18,64	26,32	70,51
BMW i3	11,56	18,56	20,97	29,11	63,75

Taking into account the emission of greenhouse gases accompanying car and battery manufacturing, as well as fuel extraction, the actual CO emission value for the considered types of cars ranges from 16,53 to 28,48 kg CO_2/100 km for cars with electric engines and from 29,11 to 31,9 kg CO_2/100 km for driving these cars with combustion engines. CO_2 emissions for electric vehicles are therefore about 56.8% to 89.3% of gasoline engine emissions (73.4% on average).

4. Impact of electric vehicles chargers on electric power grid

In order to show the impact of the development of electromobility on the state of CO_2 emissions and the degree of load on the power network, assumptions regarding the distance traveled daily by the average car and the number of potential electric cars in Poland should be assumed. It can be assumed that potential customers of motor companies offering electric cars will not be people traveling every day no more kilometers than the range of a typical car, mainly due to the inconvenience of looking for a charging point and time spent charging the car battery on the road. Fast mid-day charging would be highly probable considered as an emergency solution, thus the load generated by external charging points might not generate a strong impact on the national power grid.

On the basis of the conducted tests, it can be stated that such a limit value is the mileage of about 200 km per day. On the other hand, electric cars, presumably will not find willingly among the travelers very few, whose savings in refueling will not return the difference between a car with a combustion engine and electric one. In this case, it is difficult to determine the objective size of the monthly limit. It was arbitrarily assumed that the lower limit of the cost-effectiveness of buying an electric car is spending on fuel less than PLN 1000 per month, or 200 dm^3 of petrol a year, according to current prices in September 2018. A light, small car is able to drive around 3000 km a year on this amount of fuel, an average of 8.2 km per day.

According to a study carried out by Santander Consumer Bank [9], passenger car drivers declare the following annual travel distances:

- 23% up to 5000 km;
- 18% between 5000 and 10000 km;
- 30% between 10000 and 20000 km;
- 8% between 20000 and 30000 km;
- 5% between 30000 and 40000 km;
- 1% between 40000 and 50000 km;
- 11% more than 50000 km (professional drivers);
- 4% drivers could not declare their annual mileage.

On the basis of the data presented and the range of effective electric car use determined above, it can be stated that a maximum of about 70% of cars driving around Poland could be replaced by electric cars (characterized by mileage greater than 3000 km and less than 70000 km per year) and their number would be 10.2 million units.
In turn, according to the forecast quoted at the beginning, by 2040, the number of electric cars in Poland would amount to 5.1 million units (35% of total).

In practice, both given numbers in the simplest way determine the potential depth of the electric car market in Poland. For the purpose of further considerations, it was estimated on the basis of the above data that the average mileage of a car from the category of vehicles potentially aspiring to be replaced by electric vehicles is 12790 km a year, i.e. an average of 35 km a day.

Under average operating conditions, overnight charging of the vehicle battery will require statistically supplementing the depletion caused by a distance of 35 km. The average charging time necessary to supplement the charge level of individual car models taken into account in the previously analyzed tests is shown in table 6.

Table 6. Charging time by average daily travel distance 35 km with 2,2 kW charger.

Car model	Energy use on 35 km [kWh]	Charging time [hours
Nissan Leaf	5,71	2 hours 36 min
Renault ZOE 40	5,11	2 hours 19 min
Opel Ampera-E	5,64	2 hours 34 min
Tesla model X	8,19	3 hours 43 min
Tesla model S	7,21	3 hours 17 min
Jaguar I-Pace	9,63	4 hours 23 min
Kia Soul El.	4,76	2 hours 10 min
Hyundai Ioniq El.	4,27	1 hours 56 min
VW E-Golf	5,18	2 hours 22 min
BMW i3	5,18	2 hours 22 min

Short average daily travel distance of a statistical electric car owner results in short charging time, which can be easily fit in the night lowered electricity consumption window. However, if millions of vehicles are involved, the national power network will be heavily loaded, as it has been shown in figure 2. One million electric vehicles, the number mentioned by the Polish governmental electromobility plan [10], which should be achieved by 2025, will generate the demand for power of about 2200 MW when all users will plug in the basic 2,2 kW chargers to the network. The additional power consumption will make the night power valley more flat and the power consumption will be close to a daily average. It means that more power blocks will be involved in constant power demand coverage without going into reserve.

Looking further in future and considering 35% electric cars on the roads by 2040, number of no less than 5 million electric cars is taken into account. In such a case, night loading of such a number of vehicles will generate load of 11000 MW. It means clearly that Polish energy sector will require increasing its capacity by at least 50% to cover such enormous additional demand for power, however the maximal peak power demand could be smaller if the loading time will be dispersed during the 24 hours. To cover the daily demand for energy being consumed by electric cars, Polish coal power plants will combust additionally 2275 tonnes of hard coal daily in one million electric vehicles scenario and 11375 tonnes in 35% (5 million) share of electric vehicles in total number of passengers cars on the Polish roads.

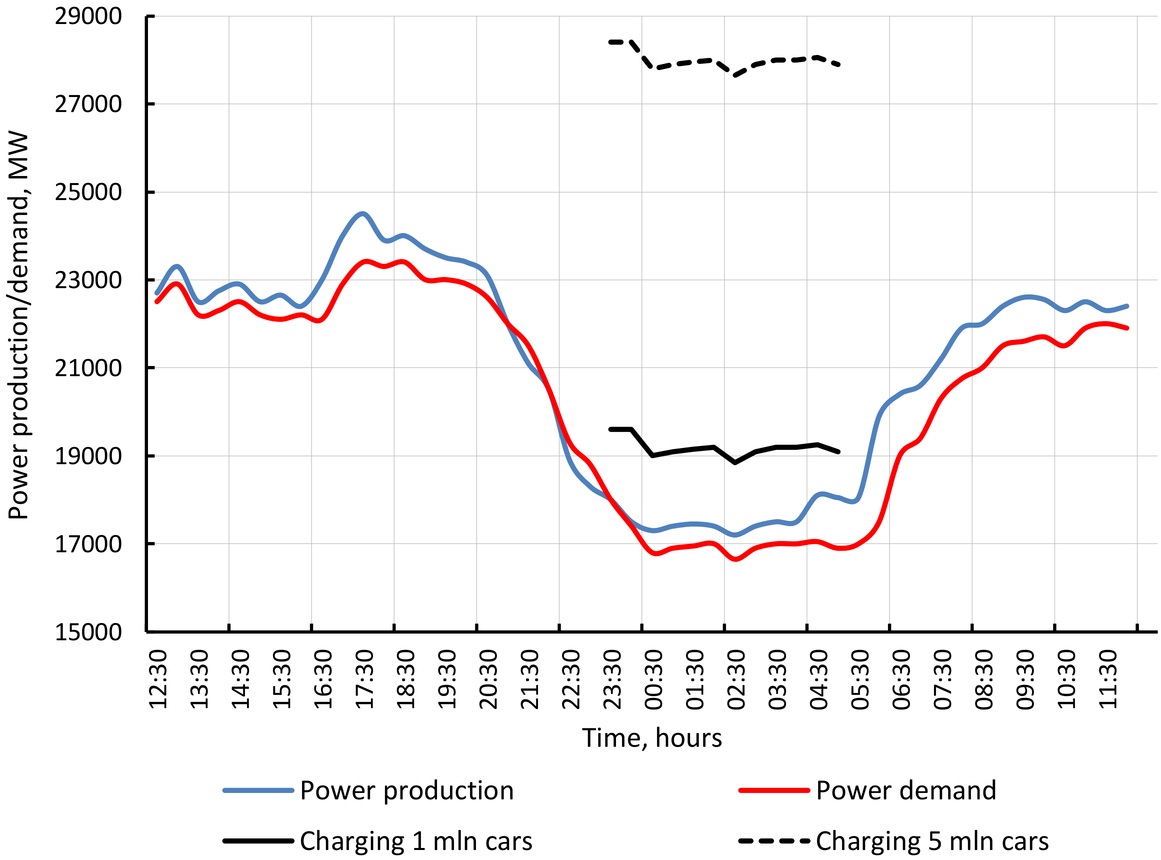

Figure 2. Power demand and production in Polish electricity network during 24 hours including impact of electric cars charging on the basis of [10].

5. Conclusions

Battery electric vehicles operate on a secondary energy source, which make them dependable on the energetic mix of a country. Considering electric cars as purely green and highly ecological means of transport is true only in countries with low energy carbonization level. In current conditions of Poland replacement of combustion engines and fuel tanks with battery packs will result in decrease of potential CO_2 emission from a car down to 67% considering energy source replacement only or down to 75% when greenhouse gas emission related to manufacturing of the vehicles is included.

Although the current level of electromobility in Poland is negligible small, the global trends suggest that in perspective of the next 20 years, the number of electric cars on the Polish roads could be estimated at the level of even 5 million vehicles.

A large problem will be preparation of the power generation industry and electricity grid for the requirements given by increasing and significant number of electric cars. Strong dependence of the Polish energy industry on coal will result in a significant increase in demand for coal, which depending on the electromobility development scenario will reach round 830 thousand tonnes per annum in one million electric vehicles scenario and 4152 thousand tonnes per annum in 35% of electric vehicles on the roads scenario. Without active measures oriented on increasing use of renewable energy sources, electromobility will plunge the energy industry depending on fossil fuels.

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