Article citation info:
Bienek F, Szczygiel I, Rutczyk B. Economical analysis of electric vehicles in Poland. Combustion Engines. 2023;192(1):55-62. https://doi.org/10.19206/CE-151941

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Combustion Engines
Polish Scientific Society of Combustion Engines

Economical analysis of electric vehicles in Poland

ARTICLE INFO

Received: 19 April 2022
Revised: 15 June 2022
Accepted: 7 July 2022
Available online: 31 July 2022

The paper presents results obtained from calculations conducted to receive information on the capability of photovoltaic systems to power electric vehicles in regular use. The annual distance travelled was divided in nine categories. Every aspect of this analysis was suitable for Polish market and parameters given by the climate that is connected with geographical location of Poland. It is worth mentioning that one of the key elements is the law for renewable energy, that is the key aspect to economical benefits that come from so called green investments. Energy law was also taken into account during this simulation. All those aspects together summarized to a conclusions that Polish market is not as competitive as other European markets when electric propulsion is present in the system.

Key words: *PV system, electric vehicles, transportation economy*

1. Introduction

The growing number of photovoltaic systems (PV) in private possession demands an analysis of using such systems for powering electric vehicles (EV) or plug-in hybrids (PHEV). Each year the number of electrified vehicles on the roads in Poland is growing but to reach expected 1 million units there some encouragement is needed. Average range of an EV is not convincing enough for Polish citizens to pay a higher price for a less versatile vehicle [1]. This is one of the aspects that is analyzed in this paper. Another one is based on PV that can charge an EV in daily routine. It is an important aspect, because this can lead to higher interest in EV as the range would not be an issue anymore. Though certain studies have been carried out on the topic of the wider usage of EVs and their impacts, such as by Szymanski et al. [2] or the study on their influence on pollution [3], the question of their basic economy of use in the Polish market, still remains open.

The paper is focused mainly on Poland but similarly irradiated regions all around the world can be taken into consideration. Scrutiny provided by these calculations can be broadly compared only when the irradiation factor is comparable. Increasing number of EVs [4] on the roads can arise demand for new PV systems and larger energy supply needs. This creates another possibility, a usage of EVs as energy storage. Although some concerns are visible at first sight, for example preparation of power grid [5], as the one currently utilized in Poland is not ready for higher demand and power supply diversity. That is the main reason to convey such calculations, because according to European lawmakers future solutions should comply with the European Green Deal. This contrast can also serve the purpose of comparing EVs and plug-in hybrids with the upcoming competition created by hydrogen cells vehicles and hydrogen combustion engines currently under development in the automotive industry.

2. Analysis of range and availability of charging stations

Considering all the aspects of using a vehicle, it is worth taking into consideration the frequently chosen summer travel destinations. In this case, analysis conducted by Statistics Poland [6] was used to determine the most popular places for spending summer holidays by Polish citizens. It can therefore be concluded that Italy is the most common foreign destination, followed by Greece. When it comes to domestic trips, the Pomorskie Voivodeship is the undisputed leader. Using this information, exemplary routes to these places were created and compared with the parameters of an electric vehicle, which were made with the use of trip planning software [7].

2.1. Route Katowice–Venice

There has been some change to this route, the use of trip planning software [7] did not take into account road works, which slightly affects the length of the route. After comparing it with the route generated in "Google Maps" [8] and comparing the travel times (estimated for journeys without stops), the author decided to take into account the differences in order to refine the analysis.

Table 1. Route details generated for ICE vehicle in "Google Maps" [8]

Route	Katowice–Venice
Time of journey	10 h 12 min
Distance	964 km
Number of breaks	2
Break duration	20 min

The travel is determined by the time of 10 h 12 min, which should be enough to cover 964 km. This time should be supplemented with data from Daimler [9], in which it is mentioned that the average time of refueling an ICE vehicle takes the user about 6 minutes. In order to create realistic travel conditions, this time was increased to 10 minutes, which gives a travel time of 10 h 40 min. For comparison, a simulation of driving this route with two vehicles representing the electric cars was created. One of them is Nissan Leaf (40 kWh) and the other is Tesla Model 3 Long Range (75 kWh). Additional information is a different distance (966 km) in relation to the journey of ICE car.

Table 2. Route details generated for Tesla Model 3 Long Range [7]

Route	Katowice–Venice
Time of journey	18 h 36 min
Distance	964 km
Number of breaks	2
Break duration	4 h 10 min

Table 2 presents data of a journey planned in EV. Usage of chargers providing low current values (1 phase, 50 kW) was the baseline in this case.

Table 3. Route details for Tesla Model 3 Long Range with the utilization of fastcharger [7]

Route	Katowice–Venice
Time of journey	11 h 6 min
Distance	964 km
Number of breaks	1
Break duration	1 h

The situation changes significantly when we consider fast charging (3 phase, >100 kW) [10], as the model allows it. This increases the comfort of traveling due to the readiness for further travel in a relatively shorter time, but the journey is extended by 26 minutes in comparison to ICE vehicle.

Table 4. Route details generated for Nissan Leaf [7]

Route	Katowice–Venice
Time of journey	27 h 12 min
Distance	964 km
Number of breaks	3
Break duration	5 h 30 min

A dramatic change in travel time occurs when there is a difference in the capacity of the batteries and charging scheme is based at 1 phase, < 50 kW devices. This parameter is almost 50% reduced (35 kWh, when compared to the capacity of Tesla's battery that has 75 kWh), while the travel time is extended to 27 h 12 min. It is therefore highly likely that people using this mode of transport would benefit from an overnight stay during the journey due to the long duration of the travel.

2.2. Route Katowice–Thessaloniki

This route was created because of the popularity of the holiday travel destination. Many people use air transport, but some people going in this direction use road vehicles.

Table 5. Route details generated for ICE vehicle in [8]

Route	Katowice–Thessaloniki
Time of journey	16 h 8 min
Distance	1579 km
Number of breaks	4
Break duration	40 min

For comparison purposes, a route with a travel time of 16 h 8 min was selected. All mapped routes follow the same roads. By enriching this time with stops for refueling [9], as in the case of the previous route, the time is extended to 16 h 45 min.

Table 6. Route details generated for Tesla Model 3 Long Range [7]

Route	Katowice–Thessaloniki
Time of journey	32 h 19 min
Distance	1579 km
Number of breaks	3
Break duration	5 h 30 min

The course of the route allows to notice one shorter stop, this is due to the possibility of using the Supercharger charging station (3 phase, > 100 kW) because this location has a rich infrastructure of these devices although other stops require usage of 1 phase, 50kW chargers. However, as can be seen at the bottom of Table 6, the travel time is 32 h 19 min, which means that the journey lasts almost twice as long as with the use of a ICE car.

Table 7. Route details generated for Tesla Model 3 Long Range with the utilization of fastcharger [7]

Route	Katowice–Thessaloniki
Time of journey	19 h 19 min
Distance	1579 km
Number of breaks	3
Break duration	1 h 30 min

When using Superchargers (3 phase, > 100 kW), the situation improves significantly, however, one must take into account an extended travel time (in comparison to ICE). It is worth noting that the route has been extended by over 500 km compared to the previous one (from Katowice to Venice), while the duration has increased by more than 1 hour. Compared to a combustion vehicle, the difference is less than 3 hours.

Table 8. Route details generated for Nissan Leaf [7]

Route	Katowice–Thessaloniki
Time of journey	47 h 42 min
Distance	1579 km
Number of breaks	5
Break duration	5 h 30 min

The travel time is almost two days, exceeding the travel time by an ICE car by more than 31 hours. This kind of time difference can exclude a vehicle from range of interest if someone is looking for a fast mean of transport. This situation has place because of 1 phase, < 50 kW chargers used to recharge this vehicle.

2.3. Route Katowice–Gdańsk

Due to the popularity of the Pomeranian Voivodeship among people spending their holidays in Poland [6], it was chosen to analyze the route connecting the south with the north of the country.

Table 9. Route details generated for ICE vehicle in [8]

Route	Katowice–Gdańsk
Time of journey	5 h 26 min
Distance	519 km
Number of breaks	1
Break duration	10 min

In accordance with the previously adopted practice, the route should include the time for a stop to fill the tank, but the range of combustion vehicles allows one to travel this route without additional stops (if the driver's physiology allows it). The time taken for the comparison is 5 h 36 min.

The order of comparisons does not change, so in the first case the Tesla Model 3 Long Range is compiled, which (as the name of the model indicates – has a greater range) is characterized by better properties in terms of the distance that can be traveled on a single charge. The range specified by the manufacturer is 580 km, therefore, it makes it possible to cover the entire distance using only the pre-journey charging.

Table 10. Route details generated for Nissan Leaf [7]

Route	Katowice–Gdańsk
Time of journey	12 h 1 min
Distance	519 km
Number of breaks	1
Break duration	6 h 30 min

Due to the more modest range (389 km – declared by the manufacturer), it is not possible to cover the Katowice–Gdańsk route, requiring a stop (1 phase, < 50 kW charger) and an extension of the journey by 6 hours 30 minutes in order to ensure further mobility.

3. Costs comparison

3.1. Costs comparison charging station vs. household

The results developed for electric vehicles, which in this analysis would be charged using a charging station, are presented. It is worth mentioning that such stations are characterized by different charging parameters such as: direct current or alternating current and various power provided by these units: less than 50 kW, 50 kW, more than 50 kW [10, 11]. Such a difference affects the time required to charge the vehicle, but not every vehicle is adapted to such an activity, as shown in Table 12.

Table 11. Charging expenses at charging station

Vehicle	Battery capacity [kWh]	Charging cost [PLN]		
		AC < 50 kW 1 phase	DC 50 kW 3 phase	DC > 50 kW 3 phase
Nissan Leaf	40	57.20	79.60	95.60
	62	88.66	123.38	148.18
BMW i3	38	54.34	75.62	90.82
Audi e-tron	95	135.85	189.05	227.05
Renault Zoe	52	74.36	103.48	124.28
Tesla Model 3	52	74.36	103.48	124.28
	75	107.25	149.25	179.25

Table 12. Charging time

Vehicle	Battery capacity [kWh]	Charging time (according to producer) [h]		
		AC < 50 kW 1 phase	DC 50 kW 3 phase	DC > 50 kW 3 phase
Nissan Leaf	40	07:30:00	01:00:00	–
	62	11:30:00	01:30:00	No info.
BMW i3	38	04:54:00	00:42:00	–
Audi e-tron	95	08:50:00	01:24:00	00:30:00
Renault Zoe	52	20:00:00	06:00:00	–
Tesla Model 3	52	07:00:00	No info.	00:30:00
	75	09:00:00	No info.	00:45:00

Prices shown in Table 11 are calculated using values from Table 12 for a user that does not have the ability to charge EV in their household thus a charging process of 0–100% (using capacities given by manufacturer) was the benchmark for each vehicle. Large part of each price is created by parking fee that is added after 1 hour of AC charging and 45 minutes of DC charging in the amount of 0.4 PLN/min [11].

In comparison charging each of aforementioned vehicles using a traditional outlet would generate costs shown in Table 13.

Table 13. Costs of charging EV using traditional outlet

Vehicle	Battery capacity [kWh]	Cost of charging [PLN]	
		Lowest	Highest
Nissan Leaf	40	27.60	31.20
	62	42.78	48.36
BMW i3	38	26.22	29.64
Audi e-tron	95	70.30	74.10
Renault Zoe	52	35.88	40.56
Tesla Model 3	52	35.88	40.56
	75	51.75	58.50

The differences are notable, as even the most expensive option of charging the highest capacity battery (95 kWh Audi e-tron) generates costs about 1 PLN lower than charging the smallest battery (38 kWh BMW i3) at the charging station.

The density of charging stations in Poland is 0.0064 station/km^2 [12], while the density of the location of the charging stations operated by Orlen, taken into account in the calculations, can be seen in Fig. 1.

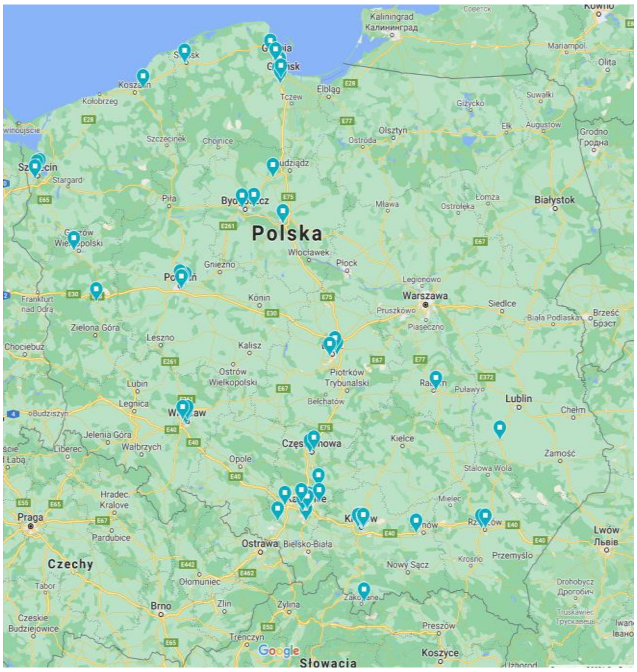

Fig. 1. Map of charging stations in Poland (provided by Orlen)

3.2. Costs comparison – ICE vehicles vs. EVs

Lists of cars has been prepared to present the costs and allow to clearly determine which vehicle is the cheapest in operation. This comparison refers only to the costs related to the source of power, all costs related to the depreciation of the vehicle are omitted, i.e. the costs of repairs, tire replacement, services, etc. The vehicles selected for this work allowed for the creation of four groups that are different from each other primarily by the segment they represent. There is also a difference between vehicles when it comes to the aspect of positioning certain vehicles as belonging to the premium segment, however this is not a measurable value and therefore it was not a parameter of this comparison.

The first group consists of representatives of the urban segment, otherwise known as the A and B segments. A characteristic parameter of these vehicles is their size and usually low power, due to the orientation of these cars towards economy, cost-effective use in the city and their easy use in such an environment. The performance is therefore not the determining aspect. It is also worth noting that vehicles in this segment are used in Poland as a means of transport for the whole family, even over long distances, which is a direct result of the ratio of purchase and use costs to the wealth of citizens.

Comparison presented in Table 14 shows that vehicles using combustion engines are able to compete directly with electric vehicles, if we take into account the economic conditions for charging vehicles with the use of charging stations available in the municipal infrastructure. This situation was taken into account due to the availability of such a solution for every user of an electric vehicle, regardless of the place of residence.

Table 14. Costs comparison – segment A and B

Vehicle	Propulsion type	km/PLN
Mini One	Petrol	3.42
Peugeot 208	Diesel	4.64
Hyundai i10	Petrol	3.97
Renault Zoe	Electric	3.82
BMW i3	Electric	3.47

Another group that has been generated for the purpose of comparison are compact vehicles, also referred to as the representatives of the C segment. These vehicles are quite small when it comes to external dimensions, but inside these vehicles are more spacious than products presented in Table 14. Such vehicles are undoubtedly suitable to travel long distances, because they allow four adult passengers to be comfortably carried with their luggage.

Table 15. Costs comparison – segment C

Vehicle	Propulsion type	km/PLN
Honda Civic 5D 2021	Petrol	2.59
Skoda Octavia IV 2.0 TDI	Diesel	4.75
Nissan Leaf (40 kWh)	Electric	4.89
Nissan Leaf (62 kWh)	Electric	3.56

This segment already shows a certain difference when we take into account the cost of 1 km, but these are not significant values, especially taking into account the prices of vehicles (in the case of electric vehicles they are much higher than in the case of internal combustion vehicles). It is also worth noting that a diesel vehicle (in this comparison – Skoda Octavia) generates lower travel costs compared to a gasoline engine vehicle. In direct competition with the more economical version of an electric vehicle, the situation for this segment differs significantly from, what was expected, the situation that takes place in the A and B segments. It can be concluded directly from the costs that only the diesel drive is an economic competition for the electric drive (in this comparison the Nissan Leaf with a 40 kWh battery).

Table 16 presents the representatives of another popular segment among the cars selected by customers, both new and used vehicles. Two vehicle models in two different configurations were compared.

Table 16. Costs comparison segment D

Vehicle	Propulsion type	km/PLN
BMW 318i	Petrol	3.09
BMW 316d	Diesel	4.06
Tesla Model 3 (52 kWh)	Electric	3.24
Tesla Model 3 (75 kWh)	Electric	3.24

The last group created for direct comparison is a very popular SUVs segment. This type of cars are intended to serve its owner in many different situations, as the abbreviation stands for Sport Utility Vehicle. Versatility brings slightly increased operating costs, which can be seen in Table 17.

Table 17. Costs comparison segment SUV

Vehicle	Propulsion type	km/PLN
Audi Q5 45 TFSI	Petrol	2.29
Audi Q5 35 TDI	Diesel	3.48
Audi e-tron	Electric	1.83

Multitude of applications for these vehicles also entails higher costs when it comes to traveling any given distance. In this case, the vehicle with electric drive is the least favorable, and its weight contributes to this, which directly affects the range offered by this solution. The difference here comes up to 1.65 km/PLN, which places this segment in the middle of the rate when it comes to coverage for PLN. Although the direct comparison of the values for the km/PLN parameter is definitely unfavorable for this segment, which allows to conclude that it is the least economical choice among those compared in this analysis.

4. PV system as charging source for EVs

Analysis of PV system usage to charge EVs was taken into consideration after comparing prices of the ICE counterparts and energy supply delivered by using public charging stations. Economical advantage provided by EVs were not significant and in some cases ICE vehicles are more budget friendly, which brings into question whether PV is the solution to this problem and what parameters should it fulfill to become a competitive option of transportation in the polish conditions.

4.1. Region of application

The regions chosen to investigate whether the PV system is suitable to power homestead and charge an EV are the three examples of irradiation diversity in Poland. Kołobrzeg presents the least solar radiation recorded during observation time, Katowice is the average irradiated region and Racibórz has the highest rate of sunlight according to the Ministry of Investment and Development [13] all of the parameters are presented in Fig 2. Data collected for the aforementioned regions can be a representation of large part of Europe according to Śmierzchalska et al. [14], thus making this paper applicable for different consumer markets.

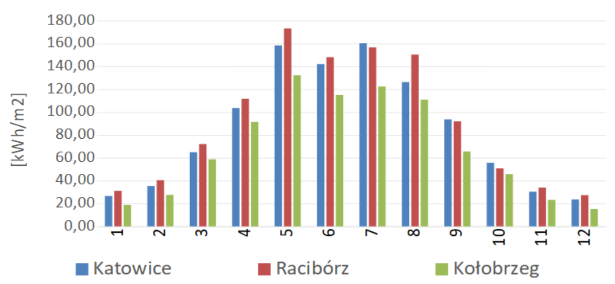

Fig. 2. Radiation magnitude for investigated regions (numbers at X axis represent months)

Summary of annual irradiation can give an insight to characteristics of each region. Kołobrzeg as the least irradiated city in this set is estimated to collect about 826.07 kWh/annum/m^2, Katowice is estimated to collect about 1019.70 kWh/annum/m^2 that is just above the average result for the territory of Poland and Racibórz can generate up to 1086.73 kWh/annum/m^2 [13].

4.2. PV system performance

Calculations were provided using PV system with nominal power of 10 kW, which is the highest power output for private use in Poland securing the highest power return rate possible. This kind of installation can also supplement the energy grid with its energy production. Polish law regulations create the possibility to use up to 80% of the power provided to power grid (by the prosumer from PV installation). In further calculations data from Gil and Wurfel [15, 16] is used as it is the most precise showing not only monthly intensity of radiation but also values recorded in time lapse, which were collected over the course of 30 years.

$$\eta_{ameff} = \eta_{pan} \cdot \eta_{inv} \cdot \eta_{am} \quad (1)$$

where: η_{ameff} – amended value of system efficiency, η_{pan} – efficiency of PV panel, η_{inv} – efficiency of inverter, η_{am} – amended coefficient.

Implementing the amended value of system efficiency for each month the values create efficiency of given system according to weather each month. Weather conditions such as temperature, humidity, precipitation were taken into account. This procedure helps to model the conditions of real environment in given area. Values obtained by calculations are presented in Fig 3. Values obtained from Daimler [8] and from formula (1) were used to calculate the amount of energy produced by the PV system taking into consideration the area of PV panels that were used in this simulation (49.5 m^2) suggested by Soleco [17], all three cities mentioned in chapter 4.1 were used to calculate the amount of energy that is possible to generate by such an installation.

$$E_m = \eta_{ameff} \cdot R_m \cdot A \quad (2)$$

where: E_m – energy produced in a period of one month [kWh], η_{ameff} – amended value of system efficiency, R_m – monthly irradiation [kWh/m^2], A – area of PV panels [m^2].

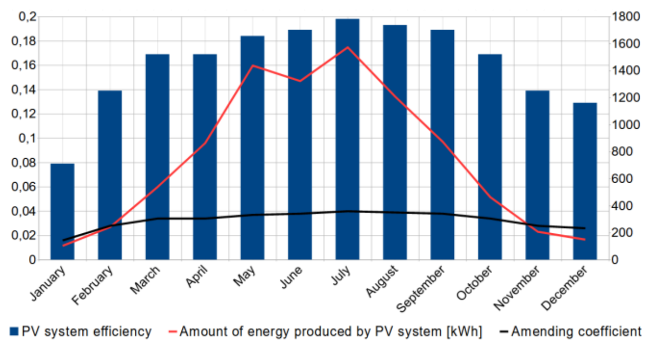

Fig. 3. PV system parameters (numbers at X axis represent months)

5. EV's market and energy demand

An important feature of a personal vehicle is mobility and independence. This chapter provides information about daily energy usage of 7 most popular EVs in Poland according to Fries et al. [2]. It creates an array of vehicles to compare with the ICE powered vehicles already in possession of a large number of commuters. Analysis was carried out for annual distance covered by vast majority of population, according to catalog data [19].

Table 18. Daily electricity demand for EVs

Vehicle	Battery capacity [kWh]	kWh/km	Thousand km/annum								
			2	5	8	12	17	25	30	35	40
			kWh/day								
Nissan Leaf	40	0.103	0.56	1.41	2.25	3.38	4.79	7.04	8.45	9.86	11.27
Tesla Model 3	52	0.113	0.62	1.55	2.48	3.72	5.27	7.74	9.29	10.84	12.39
Nissan Leaf	62	0.117	0.64	1.61	2.57	3.86	5.47	8.04	9.65	11.26	12.87
Tesla Model 3	75	0.129	0.71	1.77	2.83	4.25	6.02	8.86	10.63	12.40	14.17
Renault Zoe	52	0.132	0.72	1.80	2.89	4.33	4.13	9.02	10.82	12.62	14.43
BMW i3	38	0.145	0.79	1.99	3.18	4.77	6.76	9.93	11.92	13.91	15.89
Audi e-tron	95	0.229	1.25	3.14	5.02	7.53	10.66	15.68	18.81	21.95	25.09

$$M_D = \frac{C_{bat}}{R_{man}} \quad (3)$$

where: M_D – amount of electricity needed for every kilometer [kWh/km], C_{bat} – capacity of battery [kWh], R_{man} – range estimated by manufacturer.

Next step of calculations was to use (3) and calculate daily requisition for electricity, conducted using formula (4)

$$E_D = M_D \cdot D_{dist} \quad (4)$$

where: E_D – amount of electricity needed to cover the daily driven distance [kWh], M_D – amount of electricity needed for every kilometer [kWh/km], D_{dist} – daily distance [km].

Interesting conclusion comes to mind while analyzing the results. The first conclusion that appears obvious after analyzing the results is, that the heaviest car in the comparison (Audi e-tron) demands the highest power dose for every single day but right behind are Renault Zoe and BMW i3 which are both small and light (for EV standards) vehicles although one needs 0.53 kWh and the other 0.46 kWh (for annual mileage of 2000 km) less than the heavy Audi SUV. Growing number of kilometers generates higher differences between each vehicle, worth considering is the capacity of battery it indicates how often it is necessary to charge particular vehicle during given distance.

Table 19. Energy available to charge EV

Month	Amount of energy [kWh]
January	83.40
February	194.19
March	432.43
April	691.54
May	1150.41
June	1058.95
July	1258.88
August	966.39
September	699.02
October	371.78
November	166.64
December	120.03

Using the data presented at Fig. 3 and in Table 18 calculations that analyze how much kilometers it is possible to cover when one uses whole electricity produced by PV system in Katowice region were conducted. Including return factor of 0.8 and area of PV system mentioned in paragraph 4.2 results are as follows.

Combining results from Table 18 and 19 it was possible to calculate distance that can be covered by three exemplary cars: Nissan Leaf, Tesla Model 3 Long Range and Audi e-tron every month using the equivalent of power produced from solar energy.

An aspect of economy and difference between EV and ICE cars can be analyzed according to data received from examples shown in Table 20. Comparison fuel powered cars to EV's was based on models and specification from paragraph 3.2.

Table 20. Monthly distance provided by PV system for EV

	km/month		
Month	Nissan Leaf	Tesla Model 3	Audi e-tron
January	809.66	646.47	364.17
February	1885.31	1505.33	847.98
March	4198.37	3352.18	1888.35
April	6713.97	5360.77	3019.82
May	11169.06	8917.93	5023.64
June	10281.11	8208.95	4624.26
July	12222.15	9758.77	5497.30
August	9382.45	7491.42	4220.06
September	6786.57	5418.73	3052.47
October	3609.48	2881.99	1623.48
November	1617.82	1291.75	727.67
December	1165.34	930.46	524.15

Significant savings can be achieved when one uses PV system to power an EV, but amounts from Table 21 and 22 are extreme cases because these show annual distances equal to 31 to 69 thousand kilometers. Usually that kind of distance is covered by average citizen in 3 to 6 years time.

Table 21. Economical savings provided by PV system usage to power EV petrol vehicles compared

	PLN/month		
Month	Honda Civic	BMW 318i	Audi Q5 TFSI
January	311.72	209.07	158.89
February	725.85	486.82	369.97
March	1616.37	1084.10	823.89
April	2584.88	1733.67	131.55
May	4300.09	2884.06	2191.81
June	3958.23	2654.78	2017.56
July	4705.53	3155.99	2398.47
August	3612.25	2422.72	1841.21
September	2612.83	1752.42	1331.79
October	1389.65	932.04	708.32
November	622.86	417.75	317.48
December	448.65	300.91	228.69

Table 22. Economical savings provided by PV system usage to power EV Diesel vehicles compared

	PLN/month		
Month	Skoda Octavia	BMW 316d	Audi Q5 TDI
January	170.35	159.23	104.70
February	396.67	370.76	243.79
March	883.34	825.64	542.90
April	1412.62	1320.36	868.20
May	2349.97	2196.49	1444.30
June	2163.15	2021.87	1329.47
July	2571.54	2403.58	1580.47
August	1974.07	1845.14	1213.27
September	1427.89	1334.63	877.59
October	759.43	709.83	466.75
November	340.39	318.16	209.20
December	245.19	229.17	150.69

6. Solar panels area to fulfill the demand of an EV and an average household

Popularity of PV systems can be an asset worth considering, especially when someone is thinking about purchasing an EV. The following section contains information and data that verify how large of a solar array is needed to cover the need for electricity of an average household in Poland.

These calculations were conducted using data from the Polish Statistical Survey [19] and setting the average demand for electricity at 3500 kWh annually for a household. Given the aforementioned information the author performed simulations to achieve data that represents the area of solar panels needed to state all requirements linked to energy supply.

$$Y_E = E_D \cdot 365 \tag{5}$$

where: Y_E – annual energy demand of an EV [kWh], E_D – amount of electricity needed to cover daily driven distance [kWh/days].

EVs from two opposite points of spectrum were selected as the benchmark, to represent whole spectrum of energy usage generated by daily utilization of these vehicles**.**

The first finding that comes to mind after comparing the results is that as the annual mileage increases the demand for electricity grows heavily. Even the most economical vehicle from the array compiled in Table 18 requires energy from at least 20 m^2 of photovoltaic panels (case for 2000 km of annual travel). This occurs in the most irradiated city in Poland [13], and as it comes to the least irradiation (Kołobrzeg) the area increases to 30 m^2.

EV with higher demand for energy requires an installation of at least 25 m^2 that generates higher cost of such system and when this vehicle is used more intensively even the largest area of photovoltaic panels is not able to sustain the delivery of electricity needed. This means either the owner is going to create larger installation and receive only 0,7 of what has been produced or decides to exploit a system of power output up to 10 kW and feeds the remaining need from the power grid purchasing energy at regular prices.

7. Summary

Summarizing all obtained parameters of PV system usage, few conclusions can be made. At first the user needs to define if the system should support or be the only source of energy for the given household. In case such system is being built to be the sole source of energy, the size of the installation should be increased significantly over standard system recommended for an average household. This implicates larger number of solar panels and thus the price of whole unit is going to rise, changing the time of payback considerably. The second factor that is considered as the one responsible for price increment is the energy storage unit. Relative high price of this units is dictated by development stage of the technology connected to this sector and only upcoming innovations in battery production and materials used to create the storage can make the battery a competitor as it comes to price trade at the market.

According to calculations that compare using PV system to charge electric vehicle it can be noticed that large amount of monthly generated energy is consumed by this activity. Time required to generate enough savings to pay for the investment is estimated for 6–7 years (considering no further investments are needed and no damage to system is encountered) [20]. Given that not only EV usage should be powered by such system, a larger area of solar panels is needed. This complicates situation for individual user, because the power available to return from power grid reduces from 0.8 of produced energy to 0.7 [21]. The difference between these factors reduces savings and it can extend the return time significantly.

As the market of PV systems dynamically changes, constant observation and analysis is needed to encounter the most cost-effective method of energy generation.

Nomenclature

EV electric vehicle
ICE internal combustion engine
PHEV plug-in hybrid vehicle

Bibliography

[1] Friesa M, Kerlera M, Rohra S. et al. An overview of costs for vehicle components, fuels, greenhouse gas emissions and total cost of ownership update 2017. https://steps.ucdavis.edu/wp-content/uploads/2018/02/FRIES-MICHAEL-An-Overview-of-Costs-for-Vehicle-Components-Fuels-Greenhouse-Gas-Emissions-and-Total-Cost-of-Ownership-Update-2017-.pdf

[2] Szymanski P, Ciuffo B, Fontaras G, Martini G, Pekar F. The future of road transport in Europe. Environmental implications of automated, connected and low-carbon mobility. Combustion Engines. 2021;186(3):3-10. https://doi.org/10.19206/CE-141605

[3] Gis M, Bednarski M, Lasocki J. Determination of pollutant emission of electric vehicle in real traffic conditions in Poland. Combustion Engines. 2019;178(3):9-14. https://doi.org/10.19206/CE-2019-302

[4] Samar Vehicle Market Research Institution. https://www.samar.pl/__/3/3.a/111495/3.sc/11/Ponad-22-tys--wtyczkowozów---stan-parku-na-koniec-lutego-2021-roku.html?locale=pl_PL

[5] Kapustin NO, Grushevenko DA. Long-term electric vehicles outlook and their potential impact on electric grid. Energ Policy. 2020;(137):111103. https://doi.org/10.1016/j.enpol.2019.111103

[6] Statistics Poland „Tourism in 2019". Rzeszów, Warszawa 2020.

[7] PlugShare. https://www.plugshare.com

[8] Google maps. https://www.google.pl/maps

[9] Mercedes-Benz Group Media. https://www.media.daimler.pl/problemy-z-adowaniem-stereotypy-i-rzeczywistosc/ (accessed on 23.03.2021)

[10] Dujic D. Electric vehicles charging – an ultrafast overview. International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management. Shanghai 2019. https://infoscience.epfl.ch/record/267807

[11] PKN Orlen Poland Price list for EV charging https://orlencharge.pl/#oferta (accessed on 23.03.2021)

[12] Guziński J, Adamowicz M, Kamiński J. Infrastruktura ładowania pojazdów elektrycznych. Automatyka, Elektryka, Zakłócenia. 2014;1(15):74-83.

[13] Polish Ministry of Investment and Development. https://archiwum.miir.gov.pl/strony/zadania/budownictwo/charakterystyka-energetyczna-budynkow/dane-do-obliczen-energetycznych-budynkow-1 (accessed on 09.04.2021)

[14] Śmierzchalska P, Chmielowiec M. Mapa usłonecznienia w Polsce. Pomerian Academy in Slupsk. Slupsk 2015. https://kierunkizamawiane.apsl.edu.pl/pliki/czystaenergia/raport4_II.pdf

[15] Gil P. Roczne wyniki pomiaru sprawności amorficznych kolektorów fotowoltaicznych w Rzeszowie. Rynek Energii. 2015;(4):75-83.

[16] Würfel P. Thermodynamic limitations to solar energy conversion. Physica E. 2002;14(1-2):18-26. https://doi.org/10.1016/S1386-9477(02)00355-7

[17] Soleco Polska. https://www.kolektory.com/instalacje-fotowoltaiczne-ceny/instalacje-fotowoltaicznececeny/zestaw-o-mocy-10-kw.html (accessed on 12.04.2021)

[18] Statistics Poland. Energy consumption in households in 2018, Warsaw 2019.

[19] Fotowoltaika. https://fotowoltaikaonline.pl/kalkulator

[20] Ustawa z dnia 20 lutego 2015 r. o odnawialnych źródłach energii. Dz.U. 2015, poz. 478, rozdz. 2, art. 4, ust. 2, Chancellery of the Sejm, 2015.

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