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# Power System Preparedness for the Challenges of Electric Mobility in Passenger Transport

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***Abstract:***

***Purpose:*** *This article assesses the readiness of the National Power System (NPS) to support the growing adoption of electric vehicles in Poland. It analyzes the impact of electromobility on energy demand, grid stability, and infrastructure. The primary objective is to evaluate whether the NPS can accommodate one million electric vehicles. The study identifies potential risks and highlights areas requiring further development.*
***Design/Methodology/Approach:*** *The analysis is based on statistical data and industry reports concerning both the NPS and the electric vehicle (EV) market. Two scenarios are examined: the current situation with approximately 80,000 vehicles and a projected scenario involving one million cars. Estimation methods based on urban population and vehicle counts are employed. The research also considers charger capacity and the potential for grid congestion.*
***Findings:*** *Although the current impact of electric vehicles (EVs) on overall energy consumption remains limited, a fleet of one million EVs could have a substantial local effect. Large urban areas are at risk of grid congestion during peak hours, and uncoordinated charging may reduce available power reserves. Smart charging strategies and vehicle-to-grid (V2G) technologies can help mitigate these challenges.*
***Practical Implications:*** *Expanding charging infrastructure and implementing intelligent energy demand management are essential. Investments in smart grids and energy storage systems are necessary to support EV integration. Operators should plan for power balance and maintain adequate system reserves. These findings provide valuable insights for shaping energy and urban policy.*
***Originality/Value:*** *This article presents a technical, energy, and regulatory analysis of electromobility in Poland. It distinguishes itself with a realistic approach based on national data. The analysis includes a novel assessment of local grid load, providing actionable recommendations for operators and policymakers.*

***Keywords:*** *Electromobility, electric car, system management, passenger transport.*

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***Paper Type:*** *Research article.*

## 1. Introduction

From the perspective of managing the resources of economic and commercial systems, including the electricity supply system, electromobility presents a significant challenge. Due to its broad impact and the parameters of power and electricity, electromobility must be considered within the context of the entire national power system (NPS). The most important state-owned company in the Polish National Power System is PSE S.A. (Polskie Sieci Elektroenergetyczne S.A.), which manages key transmission networks across the country.

In Poland, the development and operation of infrastructure for alternative fuel use in transportation are primarily regulated by the Electromobility and Alternative Fuels Act of 11 January 2018 (Act, 2018). The main aim of the Act is to increase the number of electric vehicles (EVs) and to develop charging and refuelling infrastructure for alternative fuels.

Assuming an average passenger car mileage of 20,000 km and an average device energy consumption of 15 kWh/100 km, one car's electricity consumption equates to 3 MWh. Given the reported increase in electric cars in Poland (Business Insider, 2024), the energy needed to power them amounts to 3 TWh per year. This corresponds to an average continuous active power draw of 342 MW from the power system.

Using different average electricity consumption rates, we find that for 12 kWh/100 km, the consumption is 2.4 TWh/year, and for 20 kWh/100 km, it is 4 TWh/year for one million cars. In 2024, electricity consumption in Poland was 168.956 TWh, while energy production was 166.990 TWh (PSE S.A.).

Assuming an energy requirement of 3 TWh for one million electric cars, this would represent a 1.77% reduction in energy consumption and a 1.79% reduction in energy production in 2024. Therefore, one million electric cars would consume roughly 2% of Poland's total electricity.

Although this value may seem small, the time needed to charge the vehicles and the concentration of charging points in urban areas could cause local issues and electricity shortages. The situation in Germany in 2022 and 2025 exemplifies the serious risk of energy shortages in the power system. Faced with potential grid overloads, TransnetBW asked residents of Baden-Württemberg to reduce energy use during peak hours (T- Online, 2025; Modzelewski, 2025; SWR, 2024).

Beyond the danger of power outages, an important concern is the possible decline in electricity quality caused by receivers with rectifying properties operating (Kawałkowski *et al.,* 2018; Wojciechowski *et al.,* 2018; Wojciechowski *et al.,* 2024). These challenges are also discussed in energy adequacy assessments and forecasts for various countries (Polskie Sieci Elektroenergetyczne, 2024; Kubicki, 2024).

## 2. Electromobility in Poland: A Qualitative and Quantitative Analysis of Passenger Cars

As in other countries, passenger vehicles in Poland that use electric propulsion fall into one of the following categories (Ehsani *et al.,* 2018; Larminie *et al.,* 2012):

- BEVs (Battery Electric Vehicles): these vehicles do not have an internal combustion engine and rely solely on electricity stored in batteries that are charged from an external power source. Advantages include an absence of harmful emissions, the elimination of the need for refuelling and oil changes, convenient home charging, smooth and rapid acceleration, and reduced operating costs. Disadvantages include a shorter driving range compared to vehicles with internal combustion engines and a higher initial purchase price. However, this cost difference is usually offset within two to three years due to fuel savings.
- PHEVs (Plug-in Hybrid Electric Vehicle) are conventional cars that are partially electric and can be connected to an external power source. They can be connected to an external power source. They are designed for battery operation and can travel 30–50 km without using the combustion engine. The electric and combustion engines can operate separately, so with proper charging, only the electric engine can be used, similarly to BEVs. Advantages of this technology include additional range compared to electric vehicles (BEVs) and fuel savings compared to vehicles powered solely by the engine. Disadvantages include exhaust emissions, the need for fuel and oil changes, and higher operating costs than for electric vehicles (BEVs) and traditional hybrid vehicles (HEVs).
- HEVs (Hybrid Electric Vehicles) are the most basic type of full hybrid vehicle. These vehicles use energy from both an internal combustion engine and an electric motor. Their batteries cannot be charged from external sources, but instead use energy recovered during braking, deceleration, and manoeuvres such as approaching intersections. Advantages of hybrid vehicles include longer range than battery electric vehicles (BEVs), lower fuel consumption and lower exhaust emissions compared to vehicles powered solely by an internal combustion engine. Disadvantages include pollutant emissions, a complex design, higher operating costs than BEVs, and a lack of convenient home charging.
- FCEVs (Fuel Cell Electric Vehicles) - these are vehicles that have fuel cells which use hydrogen, for example, as a battery.

The analysis of the National Power System's adaptation to the needs of the electric vehicle market focused solely on BEVs, as they are entirely electric. They rely exclusively on electricity and need to be charged from the National Power System.

Plans to reach one million EVs in Poland specifically target this type of vehicle.

At the end of December 2024, approximately 80 700 fully electric BEVs—comprising both passenger cars and commercial vehicles—were registered in Poland. Over the past twelve months, their number increased by 24 223 units, representing a 2% growth compared to 2023 (PSNM, 2025).

In total, by the end of 2024, there were 141 455 electric passenger cars on Polish roads, including 72 589 BEVs and 68 866 PHEVs. Additionally, 8 111 electric delivery vans and trucks were registered. The fleet of electric mopeds and motorcycles also continued to expand, reaching 23 456 units by the end of December, along with the number of hybrid passenger cars and delivery vans, which increased to 954 340 units.

The zero-emission bus fleet comprised 1 422 vehicles, including 1 385 electric buses and 87 hydrogen-powered buses.

From an energy systems perspective, both the quantity and capacity of electric vehicle (EV) charging stations are as important as the number and power ratings of EVs themselves. In Poland and other European countries, standardised regulations govern charging stations, specifying requirements for power output, charging duration and power supply methods. Table 1 provides detailed data on charging stations.

***Table 1.*** *Basic data on EV charging stations*

| **Charging power** | **Typical configuration** | **Charging time** |
|---|---|---|
| 3,6 kW (AC) | 230V socket / wallbox 16A single-phase | approx. 16-17 h |
| 7,4 kW (AC) | Wallbox 32A 1-faza single-phase | approx. 8-9 hours |
| 11 kW (AC) | Wallbox 16A 3-fazy three-phase (often used in Poland) | approx.5,5-6 hours |
| 22 kW (AC) | Wallbox 32A three-phase (public chargers) | approx. 3 hours |
| 50 kW (DC) | Fast public chargers | approx. 1 hour 15 minutes |
| 100 kW (DC) | Fast chargers | approx. 35-40 minutes |
| 150 kW (DC) | Super-fast chargers | approx. 25-30 minutes |
| 250 kW (DC) | Tesla Supercharger V3 / Ionity | approx. minutes |
| 350 kW (DC) | Ultra-fast chargers | approx. minutes |

***Source:*** *PSNM, 2025.*

By the end of December 2024, Poland had a total of 8,659 publicly available electric vehicle charging points (PSNM, 2025). Of these, 31% were fast direct current (DC) charging points and 69% were slow alternating current (AC) charging points with a power output of 22 kW or less. Of the publicly available charging points, 63% were „Type 2” connectors, 26% were CCS Combo 2, 10% were CHAdeMO and the remainder were Tesla connectors.

The ranking of cities with the largest number of publicly available EV charging points in July 2024 was as follows: Warsaw (594), Gdansk (300), Szczecin (266), Cracow (226), Poznan (218), Łódź (197), Katowice (196), Wrocław (181), Częstochowa (131) and Olsztyn (121) (PSNM, 2025).

## 3. Literature Review

Despite electromobility being a relatively recent research topic, the issue of managing the electricity supply system in this context is becoming increasingly important in academic and industry literature. Analyses in this field can be grouped into three main areas: adapting the national power system (NPS) to accommodate the growing number of electric vehicles; optimising EV charging; and the business models and economic aspects of electromobility.

The development of electromobility poses new challenges for the NPS, particularly in terms of integrating large numbers of EVs. The widespread adoption of electric vehicles could lead to a significant increase in grid load during peak hours, making appropriate planning and adaptation of power infrastructure essential. The literature emphasises the need to develop smart grids, integrate energy storage facilities and implement smart charging systems.

These systems can shift the charging process to periods of lower demand, thereby stabilising the network. Furthermore, vehicle-to-grid (V2G) technology can be used to enable vehicles to act as mobile energy storage devices. This supports power system balancing and increases the grid's resilience to overloads (Czyż *et al.,* 2017; Clement-Nyns *et al.,* 2011; Lund *et al.,* 2008). There are various types of charging infrastructure, including conductive charging with alternating current (AC) and direct current (DC), wireless (inductive) charging, and battery swapping systems (Gnann *et al.,* 2018; Li *et al.,* 2017; Xydas *et al.,* 2016; Huang *et al.,* 2019; Li *et al.,* 2011).

Internally, they include power and installation costs for both on-board and off-board power supplies. Integrating charging stations with renewable energy sources (RES) and energy storage systems enables grid load utilisation and optimal cost coverage.
Base station safety is regulated by technical standards. In Poland, publications include the PN-HD 60364-6:2016-07 standard and the 2019 Regulation of the Minister of Energy. Technical inspections of stations are carried out by the Office of Technical Inspection (UDT) and include checks of the technical condition, electrical measurements and parameters to ensure compliance with standards, as well as technical inspections to ensure proper operation and user safety.

The literature also extensively covers business models for charging stations. The most common approach is the pay-per-use model, where users pay only for the energy they consume. The price depends on factors such as charging power, process duration and peak hours (Zhang *et al.,* 2019; Li *et al.,* 2013; Frade *et al.,* 2011; Liu *et al.,* 2016; Sadeghi-Barzani *et al.,* 2014).

This model is characterised by simplicity and transparency for the user, but generates unstable revenue for the operator. An alternative is the subscription model, where users pay a fixed monthly fee for access to a network of charging stations or specific additional services, such as priority charging or route planning via a mobile app (Li *et al.,* 2013; Sadeghi-Barzani *et al.,* 2014).

This model promotes customer loyalty and stabilises the operator's revenue, but requires a well-developed network of charging points. Some stations also utilise a freemium or sponsored charging model, in which users benefit from free charging financed by vehicle manufacturers, shopping malls or advertising. This model primarily serves a marketing function by promoting electromobility, but it does not generate direct revenue.

An increasing number of B2B models are being developed, involving cooperation between operators and companies or fleets of electric vehicles. In these models, companies pay a fixed fee for access to a specified number of energy consumption-monitoring stations (Zhang *et al.,* 2019; Sadeghi-Barzani *et al.,* 2014). While the B2B model provides a stable revenue stream and enables infrastructure expansion to be planned, it limits access for individual customers.

The literature also discusses dynamic pricing combined with smart charging, where charging rates depend on current demand and peak hours on the electricity grid. When combined with energy storage and renewable energy sources, this model enables operators to maximise revenue, reduce energy costs and stabilise the grid. However, it requires advanced management systems and greater investment. Therefore, the choice of business model depends on local market conditions, network size, user profile, and operator strategy.

## 4. Research Methodology

The adaptation of the National Power System (NPS) to accommodate electric vehicle requirements was analyzed using statistical data primarily sourced from annual reports and publicly available industry and government databases. However, these sources generally lacked disaggregated information by city, region, or county, which limited the scope of local-level analysis.

Because most data were available only as national aggregates, indirect estimation methods were employed to assess energy demand in smaller territorial units. As a result, multiple data disaggregation approaches were implemented. One approach involved proportionally assigning values to individual cities or counties based on population size, under the assumption that population size is the primary factor in determining electricity demand for electric vehicle charging.

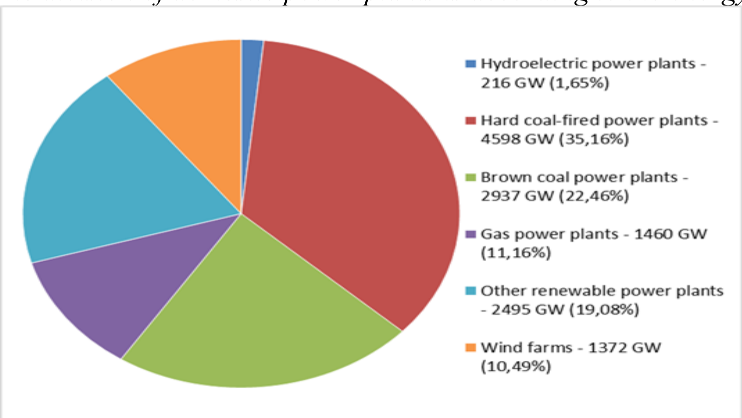
In some cases, data on the number of registered vehicles or household structure were also included to achieve a more precise distribution. While this approach enabled a preliminary estimation of the NPS load at a local level, it had significant limitations. Using uniform indicators for all cities failed to account for regional specifics such as differences in power grid density, levels of urbanisation, and local mobility patterns. The literature emphasises that obtaining local data is crucial for accurately planning charging infrastructure and assessing the impact of the growing number of EVs on different parts of the power grid.

## 5. Research Results and Discussion

The national power system consists of three primary subsectors: generation, transmission, and distribution. The generation sector includes all facilities that produce electricity, such as coal-fired, hydroelectric, photovoltaic, wind, and biomass or biogas power plants. Electricity generated by these facilities is transmitted through the transmission grid, which comprises 400 kV and 220 kV lines and substations. Polskie Sieci Elektroenergetyczne S.A. (PSE) operates this grid.

The distribution grid, consisting of 110 kV and 15 kV lines, supplies electricity to end users. The Polish energy sector is predominantly dependent on fossil fuels, with substantial domestic reserves. Hard coal and lignite contribute approximately 60% of the country's annual electricity production. Figure 1 presents a breakdown of domestic power plants by energy source.

***Figure 1.*** *The division of domestic power plants is according to the energy medium.*




***Source:*** *Author's calculations based on Electrical market, 2025.*

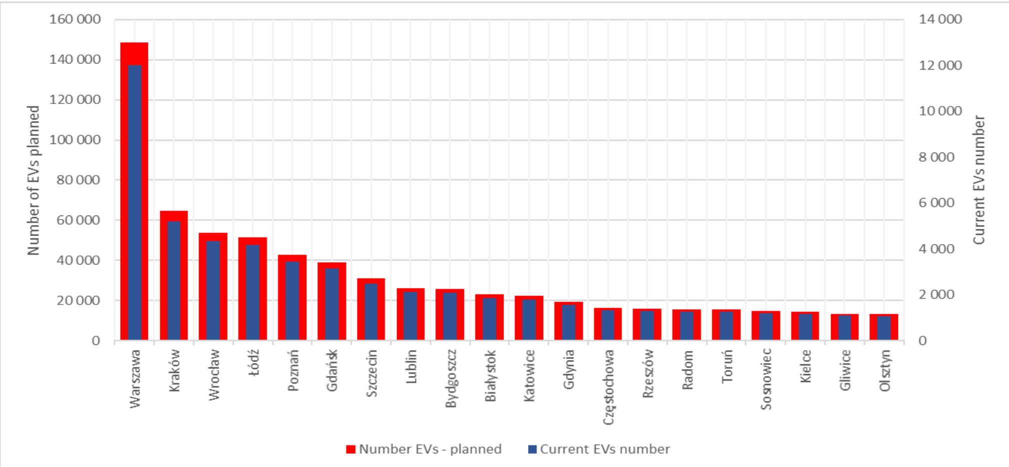
The National Power System (NPS) experiences daily fluctuations in electricity demand. During summer, demand peaks at midday and in the evening, while in winter, the highest demand occurs in the afternoon. Nighttime electricity demand remains consistently lower than production capacity throughout the year. To maintain NPS stability, coal-fired power stations operate only for limited hours during the day, resulting in increased production costs that are ultimately transferred to consumers. Under these technical and economic conditions, the integration of a new category of electricity consumers, specifically electric vehicles (EVs), warrants consideration.

To assess the NPS's capacity to support electric passenger cars, a literature review was conducted using databases and annual reports. Given that EV owners are predominantly residents of major urban centers, the analysis focused on 20 Polish cities, with each city's name and estimated population at the end of 2024 listed as follows: Warsaw (1,863,845), Cracow (809,168), Wrocław (672,882), Łódź (645,693), Poznań (536,151), Gdańsk (488,651), Szczecin (386,706), Lublin (328,305), Bydgoszcz (324,043), Białystok (290,386), Katowice (278,885), Gdynia (240,084), Częstochowa (203,615), Rzeszów (198,317), Radom (193,777), Sosnowiec (184,988), Kielce (180,530), Gliwice (168,248), and Olsztyn (166,392).

Data from the Central Statistical Office (2025) indicate that of Poland's total population of 37,489,087, only 22.28% reside in the 20 largest cities. Considering technological advancements and population density, electric vehicles (EVs) represent a relevant focus in this context. However, reliable and unambiguous statistical data specifying the number of EVs in particular cities or regions are lacking.

Based on these considerations and two EV threshold values, the current figure of 80,700 for 2024 and the planned figure of one million, the number of EVs in Poland's twenty largest cities was estimated. The calculation assumes that two-thirds of the total EVs are located within these cities, an estimate informed by available but non-systematic data on EV distribution. Figure 2 presents the EV numbers for both 80,700 and 1,000,000.

***Figure 2.*** *The number of EVs in the 20 largest Polish cities for EVs equals 80,700 units and 1,000,000 units.*




***Source:*** *Author's calculations.*

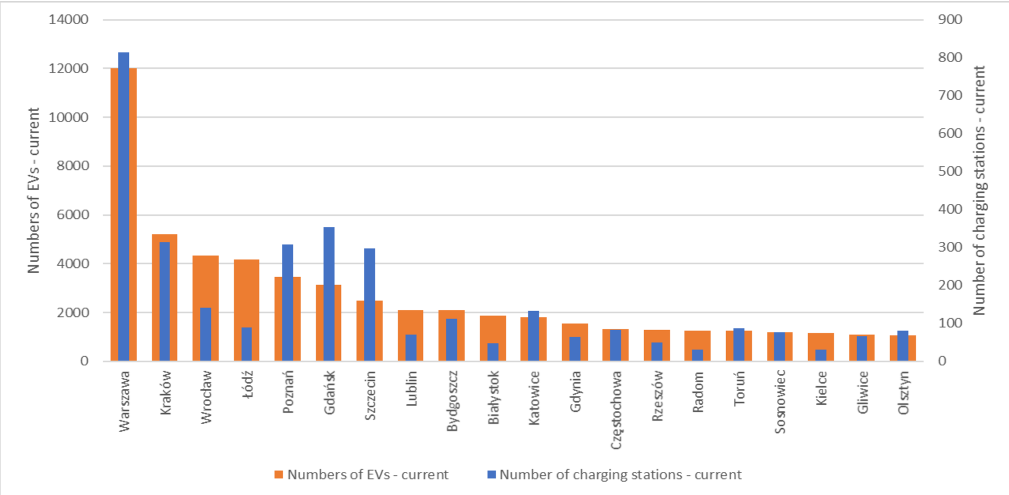
The number of charging stations is as significant as the number of electric vehicles, since the availability and capacity of charging infrastructure directly influence the demand for power from the National Power System.

Obtaining clear statistical data on the number and capacity of installed chargers in individual cities remains challenging. This challenge is compounded by the presence of individual chargers within domestic power systems, for which reliable statistics are unavailable.

For this analysis, databases including industry reports, indexes, and charging station mapping services were consulted to determine the number of publicly available chargers in the selected cities.

The reported values varied by source, reflecting differences in definitions of facilities such as „port", „outlet", and „station", as well as discrepancies in publication dates and the inclusion of company-owned chargers. Despite these limitations, it was possible to estimate the approximate number of publicly available chargers in the cities examined. Figure 3 summarises the current number of chargers and electric vehicles in each city.

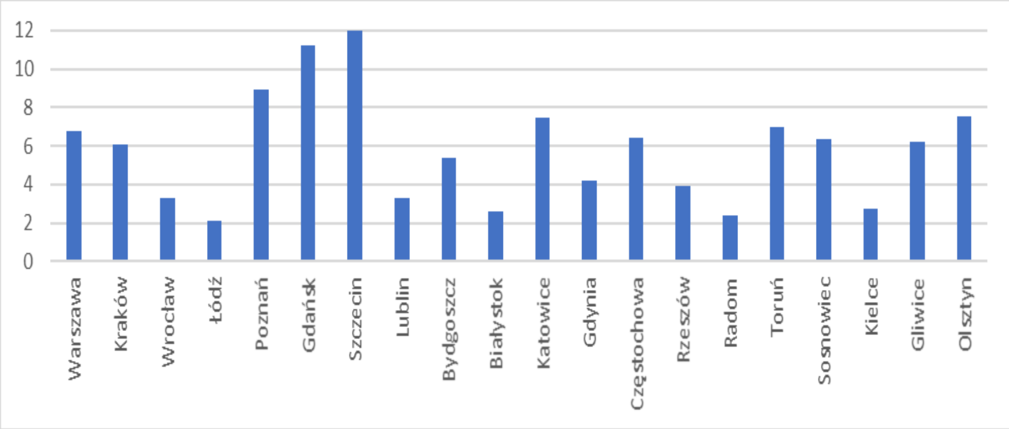
***Figure 3.*** *The number of chargers in the 20 largest Polish cities for EVs equals 80,700 units and 1,000,000 units.*




***Source:*** *Author's calculations.*

It is worth noting that the number of publicly available electric vehicle chargers in individual cities largely reflects the country's level of economic development (see Fig. 4). In cities belonging to the so-called „Eastern Wall" (Lublin, Białystok, Kielce and Radom), there are only two to three chargers per 100 EVs. By contrast, in cities located in more developed regions, such as Szczecin, Gdańsk and Poznań, this ratio is 9–12 chargers per 100 EVs.

***Figure 4.*** *The number of publicly available EV chargers per 100 EVs in the group of analysed Polish cities is shown.*




***Source:*** *Author's calculations.*

The above considerations were taken into account when calculating the cost of charging electric vehicles in the analysed group of cities. Charging time depends on battery capacity, charger power, vehicle limitations, and whether the EV is being charged using an AC system at home or a DC system for fast charging en route. The charging time (in hours) is approximately equal to the energy to be delivered (in kWh) divided by the charging power (in kW), with losses of around 5–15% taken into account, depending on the conditions.

The delivered energy is the battery capacity multiplied by (target SOC − initial SOC), where SOC stands for State of Charge. EVs are most often charged once a day, or every other or third day. This seems a practical approach when considering EV range and charging methods, i.e., charging at home. However, as EV users have very different conditions (e.g., car range, driving style, access to charging and needs), it is difficult to provide a global average.

As an estimate, drivers of cars with a range of 200–400 km will likely charge their EV every few days (i.e. every 3–6 days) based on an average annual mileage of 18,000 km (or 50 km per day). However, many owners plug their car into a home charger daily „for convenience" (top-up charging), so the number of physical connections may be high, but this does not equate to a 'full charge'. This behaviour is not consistently reported in official statistics.

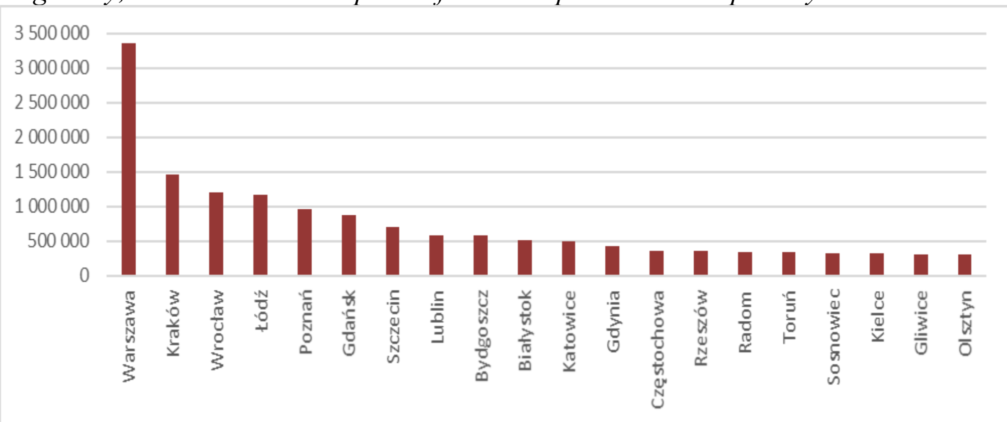
According to the Central Statistical Office, electricity consumption amounted to 155.2 TWh in 2023. The largest share of this was in the Mazowieckie Voivodeship (16.6%), followed by the Silesian Voivodeship (16.2%) and the Lower Silesian Voivodeship (9.2%). The smallest shares were recorded in the Podlaskie Voivodeship (2.0%), the Warmian-Masurian Voivodeship (2.2%), and the Lubusz Voivodeship (2.4%). Consumption by small consumers amounted to 45.8%.

The highest consumption per capita was recorded in the Opole (5,951.3 kWh), Silesian (5,818.6 kWh), and Łódź (5,012.6 kWh) voivodeships, and the lowest in the Warmian-Masurian (2,530.5 kWh), Podkarpackie (2,615.8 kWh), and Lublin (2,724.2 kWh) voivodeships. High consumption was observed in voivodeships with significant energy consumption.

The highest household electricity consumption per capita was in the Masovian (889.2 kWh), Lower Silesian (848.4 kWh) and Opole (826.7 kWh) voivodeships, while the lowest was in the Subcarpathian (522.9 kWh), Lubusz (614.2 kWh) and Świętokrzyskie (617.1 kWh) voivodeships. The data, provided by the Central Statistical Office, only covers the entire country and voivodeships. Unfortunately, data for cities is not presented.

Therefore, the average daily consumption per capita for residents of the Masovian Voivodeship was calculated based on average energy consumption. This result was also adopted for other cities in the analysed group. This value was then used to calculate energy consumption in cities. This method was then used to calculate one-day electricity consumption for the analysed group of cities. This is shown in Fig. 5.

***Figure 5.*** *Electricity consumption in the analyzed group of cities is presented for a single day, based on an assumption of 1.8 kWh per inhabitant per day.*




***Source:*** *PSE.SA, 2025.*

Electricity demand for charging electric vehicles (EVs) was estimated for both current and projected vehicle numbers, based on an average EV battery capacity of 60 kWh and the EVs population in the analysed cities. Calculations were conducted using scenarios that assumed daily charging rates of 100%, 25%, 15%, and 10%. The 25%, 15%, and 10% rates reflect actual intervals between successive electric vehicle charging cycles, as previously described.

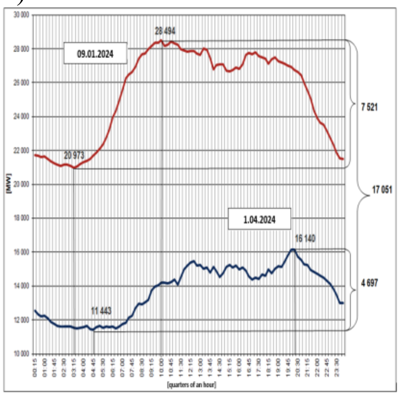
For a total of 80,700 EVs, including 53,800 in the analysed cities, EVs charging accounted for 21%, 5%, 3%, and 2% of the total electricity consumption by city inhabitants, respectively. When the number of EVs increases to one million, including 666,666 vehicles in the analysed cities, these proportions rise to 266%, 66%, 40%, and 27%. The critical issue concerns not only the total energy consumed but also the timing of consumption.

Due to the occurrence of load peaks and valleys, EVs charging can lead to filling of load valleys at night or additional load during peaks.

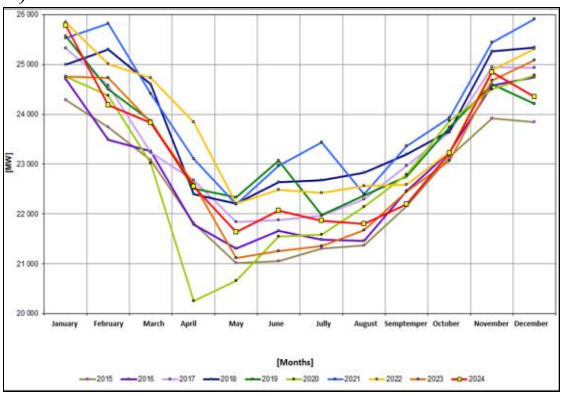
Figure 6 illustrates the national power demand curves for days with maximum and minimum demand in 2024, as well as the average monthly demand values during daily peaks on working days from 2015 to 2024 (National Power System, 2025). Comparison of electric vehicles (EVs) charging power and energy demand with National Power System (NPS) loads suggests that accommodating 1,000,000 vehicles could result in system overload.

***Figure 6.*** *National power demand curves for the day with maximum and minimum demand in 2024 -a); average monthly national power demand during daily load peaks on working days from 2015 to 2024 – b).*

a)




b)




***Source:*** *PSE.S.A, 2025.*

The safe and efficient operation of the National Power System (KSE) depends on comprehensive planning and management across multiple time horizons and operating conditions. An essential objective is to guarantee uninterrupted power and electricity supply while sustaining adequate reserve capacity, defined as the surplus generating capacity above the current system load. Reserve capacity plays a critical role during emergencies, including sudden demand surges or unexpected outages of generating units or grid infrastructure, and constitutes a fundamental component of national electricity security.

The determination of required reserve capacity depends on factors such as system size, power source structure, power unit reliability, weather conditions, and inter-system exchange balance. In operational settings, reserve capacity is typically established according to industry standards and the regulations of the transmission system operator. The National Power System (KSE) identifies three primary reserve categories: spinning reserves, which enable immediate generation increases; non-spinning reserves, which can be activated on short notice; and planning reserves, which constitute the long-term surplus of installed capacity over the system's maximum demand.

The typical spinning reserve is maintained at approximately 2–3% of current demand or matches the capacity of the largest generating unit. Under Polish conditions, this corresponds to 570–855 MW of available capacity. The N-1 criterion, which addresses the largest single failure, necessitates at least 0.86 GW of capacity to be available within a short timeframe. The operating reserve, comprising both spinning and quick-start units, should represent 5–10% of the forecasted peak load. For the Polish power system, this translates to approximately 1.42–2.85 GW.

The transmission system operator, Polskie Sieci Elektroenergetyczne (PSE), typically maintains an operating reserve of several gigawatts to compensate for unpredictable load fluctuations and sudden generation losses.

The planning reserve refers to the long-term surplus of installed capacity over peak demand. Generally accepted standards recommend a reserve margin of 15 to 25 percent, which in Poland equates to 4.27 to 7.12 GW. Despite a projected installed capacity of approximately 72 GW by the end of 2024, system security will depend primarily on the available capacity and the operational flexibility of generating units. This consideration is especially relevant given the increasing proportion of renewable energy sources, which exhibit variability and limited controllability.

The Polish National Power System experiences a maximum power demand of 28,494 MW, with the largest generating unit being the 858 MW unit at the Bełchatów Power Plant. Analysis of actual reserve levels demonstrates that, at times, the available reserve falls below thresholds considered safe.

For instance, in August 2024, the reserve dropped below 5% of demand, reaching approximately 600 MW. At present, with an installed capacity of 72 GW, the reserve exceeds 18% of current demand. However, the rapid growth in the share of renewable energy sources has led to greater generation variability, which complicates accurate forecasting of required reserve levels for both operational and planning purposes.

The calculation results presented above reflect the operating conditions of the National Power System (KSE) at a peak load of 28,494 MW. It is also necessary to assess the system's response to a potential increase in demand to 30,000 MW and to the substantial integration of photovoltaic sources, which would introduce greater variability and uncertainty in system balance.

Analysing these scenarios facilitates an evaluation of the KSE's resilience to future challenges associated with rising energy demand and the ongoing energy transition.

Assuming peak demand increases to 30,000 MW while maintaining typical reserve assumptions (2–3% for the spinning reserve, 5–10% for the operating reserve and 15–25% for the planning reserve), these values increase proportionally. Spinning reserves represent the ability to immediately increase generation and should be at least as large as the capacity of the largest unit in the system.

In this case, this corresponds to approximately 900 MW. The operating reserve, which includes spinning units and quick-start sources, should range from 1.5 GW (5%) to 3.0 GW (10%). The planning reserve, which is the long-term excess capacity required to ensure stability against potential unit failures or outages, should range from 4.5 GW (15%) to 7.5 GW (25%). These reserve levels represent the minimum requirements for ensuring the long-term security of system operation.

An alternative approach is required due to the increasing share of renewable energy sources, particularly photovoltaics and wind power. When the National Power System (KSE) becomes highly saturated with weather-dependent sources, the system operator must expand both operating and planning reserves to address greater variability and reduced predictability in generation.

With a peak demand of 28,494 MW, the operating reserve should be increased to 8–12%, equating to approximately 2.28 GW to 3.42 GW. The planning reserve should be maintained within 25–35%, or about 7.12–9.97 GW. These requirements underscore the necessity for simultaneous development of flexible conventional sources, energy storage solutions, and advanced system services. Such measures will support the KSE in maintaining stability as the share of renewable energy grows and the generation mix continues to evolve.

Analysing the impact of mass electric vehicle charging on the load of the National Power System (KSE) is an important element in assessing the system's resilience to new challenges stemming from the energy transition and transport electrification. Using the current system parameters as a reference point — peak demand of 28,494 MW and typical power reserve levels (spinning reserve of around 858 MW and operating reserve of 1.42–2.85 GW) — the potential effects of a large number of electric vehicles charging simultaneously were assessed.

The analysis considered three representative charging powers: 7 kW (AC home charging), 11 kW (AC accelerated charging) and 50 kW (DC fast charging). The additional system load was calculated depending on the number of vehicles charged simultaneously.

In a scenario involving 100,000 vehicles charging simultaneously, the load generated by the 7 kW chargers amounts to around 700 MW. This equates to 2.46%

of peak demand and remains below the spinning reserve level. The load generated by the 11 kW chargers is 1,100 MW (3.86%), which exceeds the spinning reserve but remains within the lower range of the operating reserve. By contrast, a 50 kW fast charger generates a load of 5,000 MW (17.55% of peak demand), which significantly exceeds the typical operating reserve level and leads to the need for system operator intervention.

Much more serious consequences become apparent at a scale of 500,000 vehicles. Charging at 7 kW results in an additional load of approximately 3,500 MW (12.28%), which exceeds the upper limit of the operating reserve and may require restrictions or increased energy imports. For 11 kW chargers, the load increases to 5,500 MW (19.31%), while for 50 kW fast charging it reaches 25,000 MW, approaching total national demand.

In a scenario with 1 million simultaneous charging sessions, the effects become critical: for 7 kW charging, the load is approximately 7,000 MW (24.57%), and for 11 kW – 11,000 MW (38.60%). The most extreme case, i.e., charging 1 million vehicles at 50 kW, generates an additional demand of 50,000 MW, which corresponds to 175.5% of the current national peak and exceeds the capacity of the National Power System.

The safety thresholds were determined by establishing the number of vehicles at which the spinning or operating reserve would be exceeded. For 7 kW charging, the spinning reserve is exceeded at approximately 123,000 vehicles and the operating reserve at approximately 407,000 vehicles.

For 11 kW charging, these thresholds are approximately 78,000 and 259,000 vehicles, respectively. For fast charging at 50 kW, the spinning reserve is exceeded at approximately 17,000 vehicles and the operating reserve at approximately 57,000 vehicles. These results demonstrate that fast DC charging represents the most critical load type for system stability.

## 6. Conclusions, Proposals, Recommendations

The development of electromobility in Poland represents a significant challenge in the transformation of the transport sector and is closely connected to the functioning of the national power system. Although strategic documents have been adopted and manufacturers have systematically expanded electric vehicle offerings, the current pace of transport electrification remains inadequate.

Projections of a rapid transition to electric propulsion appear overly optimistic. The continued dominance of combustion vehicles and the slower adoption rate relative to other European countries underscore the necessity for coordinated regulatory, technological, and investment initiatives.

An analysis of the impact of increasing electric vehicle adoption on the power system indicates that a moderate charging event, involving approximately 100,000 vehicles at 7 kW each, can be accommodated without significant disruptions if charging is dispersed and evenly distributed over time.

However, as the number of electric vehicles rises, hundreds of thousands of simultaneous charging sessions may exceed operational reserves. Fast direct current (DC) chargers present the highest risk of both local and national overload; several thousand 50 kW charging sessions can approach the limits of the system's spinning reserve. Initial signs of overload typically emerge in distribution networks, particularly near transformers and medium-voltage lines, before escalating to a system-wide issue.

To mitigate potential impacts, it is recommended to implement smart charging mechanisms that allow for control of start times and power levels, including delays and soft starts, as well as aggregation of charging sessions. Staggering charging hours, including night-time tariffs, off-peak promotions, and dynamic tariffs and flexibility signals, can shift a significant portion of the load off-peak.

In locations with a high concentration of chargers, the use of battery-powered storage (BESS) and local microgrids can cushion sudden charging pulses, while vehicle-to-grid (V2G) technology serves as short-term reserve and regulation. In the short term, additional flexibility is provided by increased operational reserves or quick start via gas, generators, or energy imports.

Expanding charging infrastructure requires parallel modernization of distribution networks, particularly medium- and low-voltage networks, including replacing cables, modernizing transformers, expanding transformer stations, and installing additional circuits, all while continuously monitoring grid quality parameters.

Integrating distributed energy sources with storage and charging points reduces grid load, increases the share of renewable energy in transport, and better balances demand over time, using surplus energy to charge vehicles or feeding it back into the grid during periods of increased demand.

Smart grids, which incorporate measurement systems and communication interfaces with end-user devices, are essential for the integration of distributed energy resources. These systems facilitate optimal control of infrastructure components, balance energy flows, and support flexible load management. Implementing such technologies can decrease the necessity for expensive grid upgrades as the number of fast chargers increases and can also enhance overall energy efficiency.

Achieving the goals of the Electromobility Act requires cooperation between distribution system operators and local governments in planning the locations and connection capacities of new charging points. The lack of appropriate financial and coordination mechanisms can lead to delays in infrastructure development, therefore, it is essential to create a system of incentives to support investments in network modernization and the installation of new charging stations.

In summary, the effective development of electromobility in Poland requires the parallel implementation of V2G technologies, smart grids and energy storage systems, the integration of renewable energy sources with charging infrastructure, and the introduction of market and regulatory incentives for off-peak charging. Coordinated action in these areas is essential for the full integration of the growing fleet of electric vehicles into the national power system while maintaining its stability, security, and efficiency.

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