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Energy potential and economic viability of small-scale wind turbines

Jakub Jurasz [a,b,*], Bogdan Bochenek [c], Joanna Wieczorek [c], Adam Jaczewski [c], Alexander Kies [b,d,e], Mariusz Figurski [f]

[a] Wrocław University of Science and Technology, Wrocław, Poland
[b] Aarhus University, Nordre Ringgade 1, Aarhus C, 8000, Denmark
[c] Centre of Numerical Weather Prediction, Institute of Meteorology and Water Management – National Research Institute, Warsaw, Poland
[d] School of Chemistry and Physics, University of KwaZulu-Natal, Westville, South Africa
[e] Frankfurt Institute for Advanced Studies, Goethe University, Frankfurt, Germany
[f] Gdansk University of Technology, Faculty of Civil and Environmental Engineering , Gdańsk, Poland

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ABSTRACT

Small-scale wind turbines (SWTs) have the potential to complement residential PV systems, but their feasibility is highly dependent on local wind conditions, particularly at low elevations where wind resources exhibit high spatial and temporal variability. This study evaluates SWT potential in Poland (Central Europe) using hourly wind speed measurements over six years from 269 gauging stations. A generic power curve is applied to assess wind energy generation at 173 sites with sufficient data completeness (>95 %).

The economic viability of SWTs is analyzed through levelized cost of electricity (LCOE), capture price, and self-consumption, with the latter two serving as key indicators for investors exposed to dynamic (day-ahead) electricity market prices. The results reveal that only 13 sites (7.5 %) achieve a capacity factor above 10 %, a threshold comparable to PV systems. Additionally, SWTs and PV exhibit low daily complementarity, as both technologies tend to have coinciding generation peaks around midday, which limits their combined effectiveness in hybrid setups.

While SWTs outperform PV systems in terms of annual power generation in selected locations, investments should be preceded by site-specific wind resource assessments, and support schemes must be carefully designed to avoid subsidies in low-potential areas. The findings suggest that without significant cost reductions or targeted policy incentives, SWTs are likely to remain a niche solution rather than a widespread alternative to PV.

1. Introduction

In recent years, power systems worldwide have seen a substantial increase in the installed capacity of solar PV systems [1]. This growth has been driven by the rapid decline in PV technology costs [2] and the rising variability of electricity prices [3], encouraging both households and businesses to invest in decentralized energy generation.

However, the diurnal and seasonal variability of solar energy, which often shows a weak correlation with demand, limits the efficient utilization of this energy source expressed through for example low self-consumption rates [4,5]. While daily fluctuations in solar generation can be managed with energy storage solutions [6,7], seasonal variations, particularly in regions further from the equator, present a greater challenge. To address this issue, hybrid energy systems have been widely proposed in the literature [8]. These systems integrate two or more renewable energy sources (RES) that exhibit complementary generation patterns over different timescales [9,10].

The theoretical basis for combining solar and wind energy is supported by historical data, as illustrated in Fig. 1 [11]. In Poland's winter-peaking power system, solar generation is concentrated between May and September, while wind energy dominates the remaining months, highlighting their seasonal complementarity.

The analysis presented in Fig. 1 illustrates the variability and complementarity of wind and solar power across different time scales, emphasizing their potential for balancing electricity demand and generation. The seasonal complementarity between solar and wind energy, along with the better demand-supply matching of wind generation, raises interest in the economic viability of small-scale wind turbines (SWTs). Unlike solar PV, which has been widely adopted, SWTs remain a niche technology, warranting further investigation. It is important to

* Corresponding author. Wrocław University of Science and Technology, Wrocław, Poland.
E-mail address: jakub.jurasz@pwr.edu.pl (J. Jurasz).

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note that, unlike large-scale wind farms, SWTs exhibit different generation patterns, largely due to their placement in built environments, which produces spatially and temporally complex wind patterns affected by turbulence.

The following literature review provides an overview of the state-of-the-art research on SWTs, with a focus on their techno-economic performance. It first explores the global context before summarizing existing research on SWTs in Poland.

1.1. Related literature - worldwide context

The available literature on small-scale wind turbines (SWTs) remains relatively scarce. Even in countries with significant wind resources, such as Ireland [12], microturbines have not been widely adopted, primarily due to uncertain economic viability. This economic challenge appears to be one of the biggest obstacles to widespread SWT adoption. Several studies have assessed the techno-economic feasibility of SWTs across different regions, highlighting key challenges: **Germany**: A study examined urban households [13], identifying wind speeds and urban morphology as critical factors for profitability. The findings suggest that SWTs are only cost-effective in suburban and rural areas with favourable wind conditions. **Turkey**: A study in southern coastal regions found that while SWTs could generate enough energy to meet household demand, their net present value (NPV) remained negative over a 10-year period [14]. However, within a 20-year lifespan, some investments became only marginally viable. In **Iran** multiple studies assessed SWT potential across various regions: A national-scale study [15] found SWTs were cost-effective in 30 % of locations, particularly where wind speeds exceeded 5 m/s, with 3 kW turbines identified as most suitable. A regional study in Kerman [16] found annual average wind speeds of 2.7 m/s, peaking at 4.9 m/s at noon, but payback periods exceeded the 20-year turbine lifespan, making them economically unfeasible. Another study [17] in Shahrbabak found that while large-scale wind energy was not viable due to low wind power density, SWTs for localized off-grid applications (e.g., lighting) were feasible. In Iraq SWT of capacity 50 kW were tested for two sites with capacity factors respectively 16.7 % and 18.1 % by Jadallah and Ibrahim in Ref. [18]. **Indonesia & Malaysia**: In South Sulawesi, Indonesia, wind speeds of 5 m/s were insufficient for profitability, but at 7 m/s, a 300 W turbine had a payback period of 6.6 years [19]. In Malaysia, SWTs were found not to be viable, as average wind speeds ranged from 2 to 3 m/s at 10 m above ground level [20]. Increasing tower height could improve energy capture, but the additional costs would further reduce economic feasibility [21]. **Africa**: In Egypt, SWT feasibility was assessed across 17 locations, with economic viability limited to high-wind-speed areas [22]. In South Africa, a study across 12 locations [23] found that while Port Elizabeth and Cape Town had the highest annual energy production, most sites were not viable, with payback periods between 12 and 38 years and negative NPVs. An alternative approach explored *ferris* wheel-based wind turbines, which showed some competitiveness [24]. A study conducted for Nigeria found

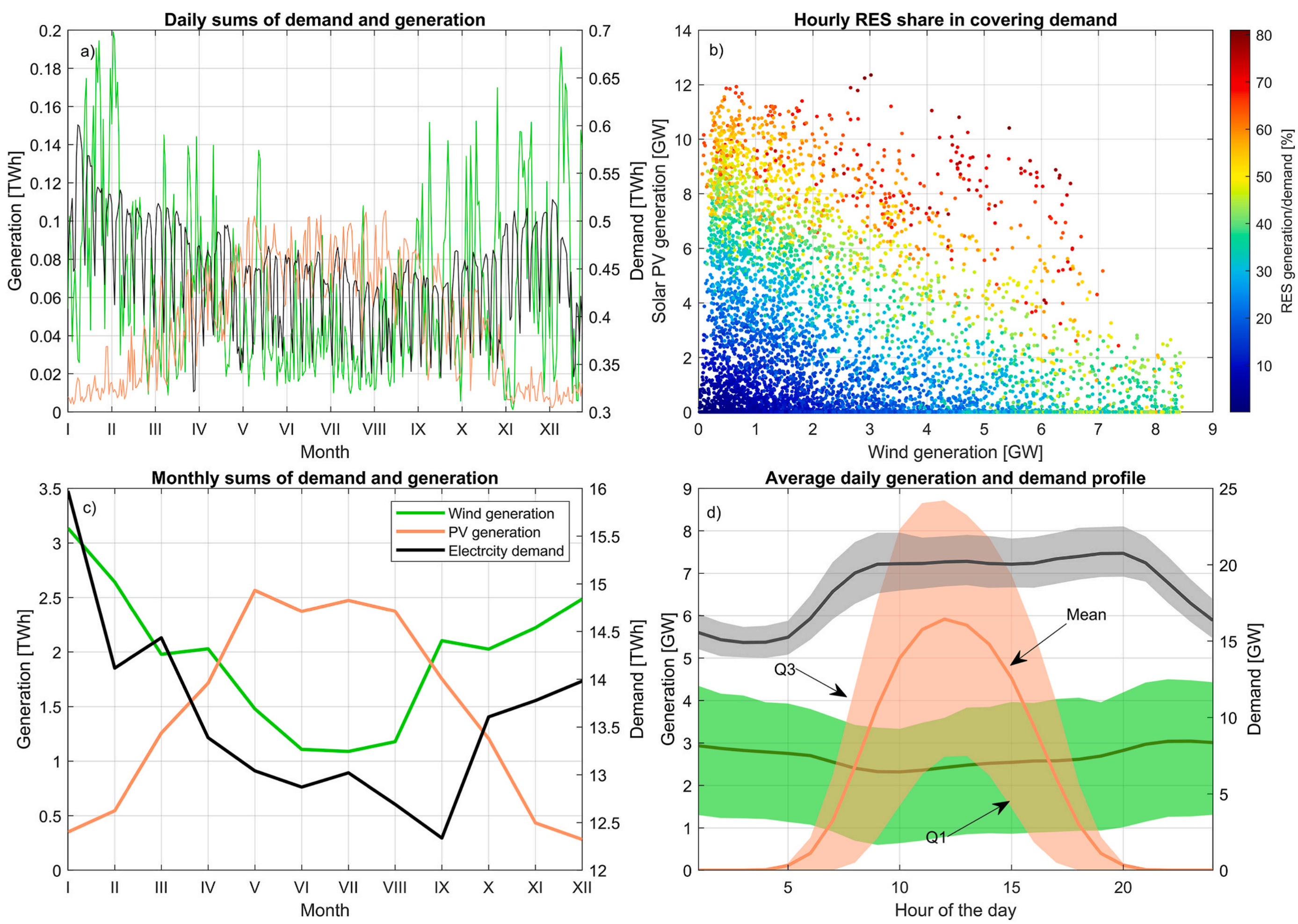

Fig. 1. Historical solar PV and wind generation juxtaposed with electricity demand on a country level from the perspective of daily (panel A), hourly (panel B) monthly (panel C) sums. Solar and wind energy complement each other on a monthly level (panel C) whereas the wind generation exhibits a much better alignment with the electricity demand. Typical daily (panel D) generation patterns reveal lower day-time generation from wind that tends to be complemented by higher solar PV generation, but it is not always true as shown on panel B in the lower left corner where simultaneous low generation from both sources is reported.

that in selected locations, the cost of electricity from SWTs could be competitive with the local grid prices [25]. **Mexico & the United States**: In Mexico, a study across 18 locations examined 28 SWT models over three years. Only two site-turbine combinations resulted in a positive NPV, demonstrating high location dependency [26]. In Oklahoma, USA, SWTs were not competitive with grid electricity, with the annual cost of a 6 kW turbine system being five times greater than purchasing electricity from the grid [27]. **Brazil**: A study assessing SWT feasibility for small businesses in three Brazilian states found low viability, with a probability of success ranging from 17 to 24 % [28]. Another study identified key variables affecting economic feasibility and concluded that investing in residential wind power had low financial viability [29].

Summarizing the global research on SWTs consistently points to significant economic challenges, with wind speed being the primary determinant of feasibility. While off-grid and specific high-wind locations may offer some viability, high investment costs, long payback periods, and low capacity factors continue to hinder widespread adoption.

1.2. Related literature – Polish context

Recent studies have assessed the energy and economic viability of SWTs in Poland, highlighting significant regional variations in feasibility: Zalewska et al. [30] analyzed SWT performance across three locations (coastal, foothill, and lowland). The coastal site demonstrated the best economic viability, with a payback period of 13 years and an electricity cost of 0.16 EUR/kWh. In contrast, the foothill and lowland sites were economically unfeasible, with payback periods exceeding 40 years and costs reaching 0.71 EUR/kWh. Augustowski and Kułyk [31] examined the economic feasibility of 10 kW wind turbines for residential use in Zielona Góra, Szczecin, and Gdańsk. The study found that without subsidies, the payback period is approximately 9 years, but with 50 % financial support, it shortens to 3–4 years. Investments in coastal regions (e.g., Gdańsk and Szczecin) were more profitable, reflecting higher wind speeds in these areas. Bukala et al. [32] compared three small wind turbine designs, concluding that the traditional bladed horizontal-axis wind turbine was the most cost-effective, offering the best return on investment. The findings suggest that SWT investments in Poland are highly site-dependent, with coastal areas showing the best feasibility. Government subsidies significantly improve payback periods, making policy support a key factor in SWT adoption.

1.3. Research question

Building on the literature review, this study aims to address key knowledge gaps by investigating the following research questions.

- What is the energy production potential of small-scale wind turbines in various regions of Poland based on historical wind speed data?
- What is the capture price of small-scale wind turbines and how does it compare to PV systems and large-scale wind turbines?
- What level of self-consumption can be observed for small-scale wind turbines depending on the load profile?
- What is the levelized cost of electricity for small-scale wind turbines?

Novel contributions:

This study provides the first temporally and spatially comprehensive assessment of the economic potential of small wind turbines in Poland. In addition to estimating the LCOE and capture price of SWTs, this work offers.

- An analysis of self-consumption rates across different load profiles to assess the feasibility of on-site utilization.
- A comparison of daily generation patterns between SWTs and solar PV, evaluating their complementarity at high temporal resolution.
- An economic comparison of SWTs, large-scale wind turbines, and PV systems from a capture price perspective.

By integrating these aspects, this study aims to provide a more detailed and policy-relevant understanding of the role SWTs could play in Poland's energy transition.

2. Methods and data

To address the research questions formulated at the end of Section 1.3 this research adopted methodology that is schematically shown on Fig. 2. The research itself was mostly based on historical meteorological data (wind speed) combined with market (electricity prices) and power system data. Following subsections describe in detail the individual steps.

2.1. Meteorological data

Measurements of wind speed from 269 stations of Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) were used in this study. This data is freely available from https://danepubliczne.imgw.pl/ [33]. As a part of National Hydrological and Meteorological Service, the IMGW-PIB follows the rules of World Meteorological Organization in terms of height, location, surrounding and measurement devices. The original data was available with a 10 minutes resolution however it was processed to hourly time step to match the demand profiles and the power system/market data. Stations with less than 5 % missing records during the analysis period (2018–2023) were selected after screening the data, totaling 173 sites selected for further study. As it will be later visible on Fig. 4 the spatial distribution of stations in Poland is not homogenous. In Southern Poland, where complex topography exists, Sudeten Mountains lacks sufficient station density to monitor diverse weather patterns accurately, in contrast with Carpathian region. The summary table containing all information concerning the meteorological stations is provided in the Appendix Table 4.

2.2. Wind turbine modelling

This study follows a widely used approach in the scientific literature [34,35] to model wind power generation by combining wind speed measurements with a wind turbine power curve. The turbine is assumed to be mounted at 10 m above ground level, matching the height of the meteorological measurements.

Wind speed is converted into power using an average power curve (Fig. 3), derived from a subset of SWTs' power curves. According to this curve, the turbine starts operating at wind speeds above 2.5 m/s and shuts down at 18 m/s, which is representative for most SWTs. It is important to note that the losses due to inverter inefficiencies, wiring, malfunctions, and equipment degradation are not included in this analysis. The calculations assume a constant air density of 1.2 kg/m^3 over the entire simulation period. For wind speeds between 2.5 m/s and 18 m/s, power generation is approximated using a fitted polynomial equation. The energy output in Fig. 3 is normalized and presented as hourly generation per kW of installed capacity under different wind speed conditions.

2.3. Capacity factor

This study quantifies wind energy generation using energy produced per unit of installed capacity (kWh/kW) over a specified integration period (e.g., day, month) and capacity factor (CF), a widely used metric for comparing energy sources across different locations. While CF is typically calculated on an annual basis, monthly CF values can also be derived to assess seasonal variability. The following equation is used to calculate the CF:

$$CF = \frac{\sum_{i=1}^{n} E_i^{Actual}}{P^{Rated} * n} \tag{1}$$

where: E_i^{Actual} – actual generation output at time step i [kWh], P^{Rated} -

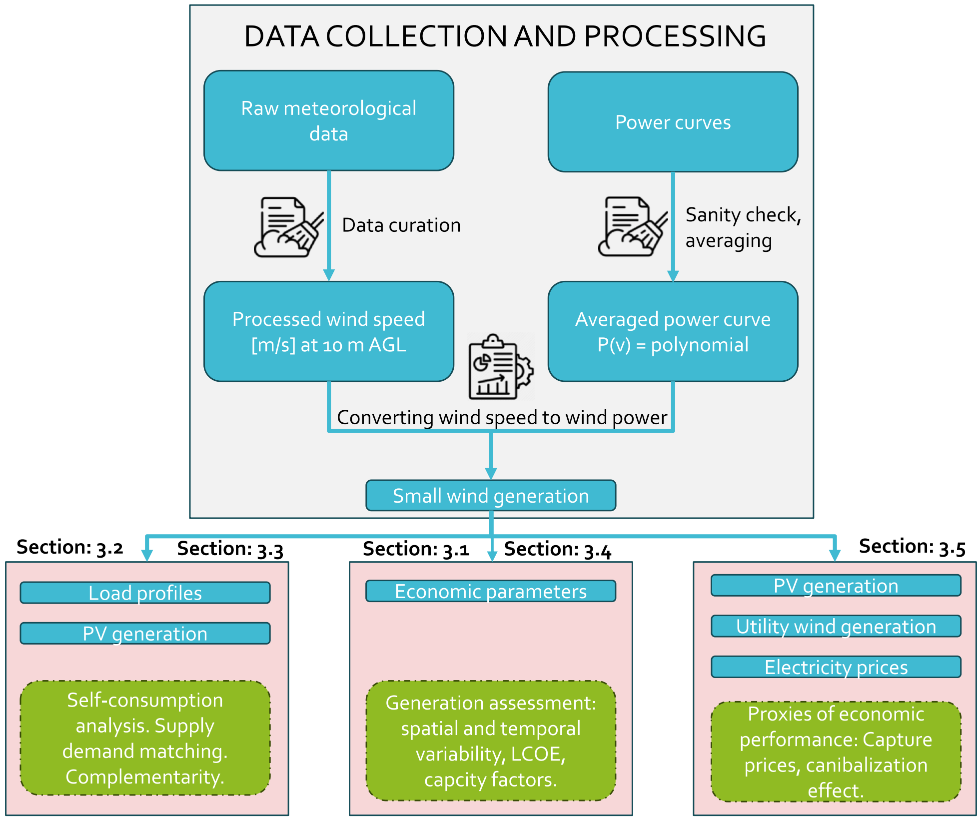

Fig. 2. An overview of the research approach adopted in this study.

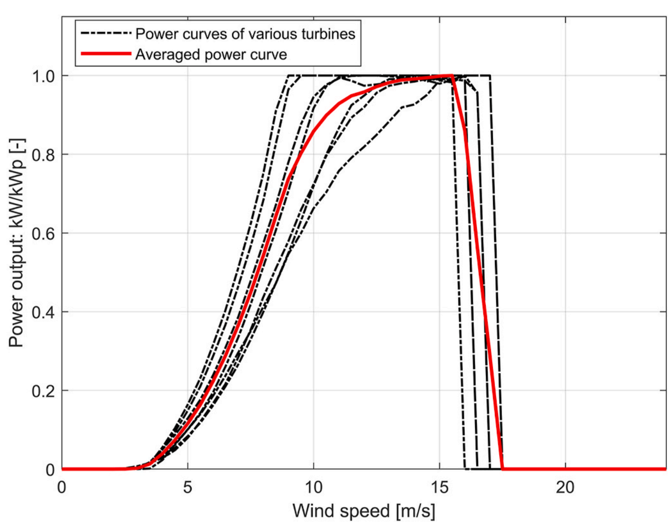

Fig. 3. Normalized power curves of several representative wind turbines (doted-black) and averaged power curves (continuous-red) adopted in this study. Power curves obtained from Ref. [36].

rated (installed) capacity of the plant [kW], n – total time periods considered [h] (e.g. 8760 h for a full year).

2.4. Self-consumption

Self-consumption from a wind turbine (or any other generator [37]) refers to using the electricity it generates to meet the on-site energy demand, rather than exporting it to the grid. This does not include the turbine's own operational power needs (parasitic load), but rather the consumption of electricity by other loads at the site, such as a household, business, or facility. By increasing self-consumption, reliance on external electricity sources is reduced. The following equation was used to calculate self-consumption (SC):

$$SC = 1 - \frac{\sum_{i=1}^{n} max\left(E_i^{WT} - E_i^{D}; 0\right)}{\sum_{i=1}^{n} E_i^{WT}} \tag{2}$$

where: E_i^{WT} – energy generated by wind turbine at time step i [kWh], E_i^D – energy demand at time step i [kWh].

Self-consumption was calculated for nine typical load profiles [38], representing different customer groups such as households, small businesses, and industries. Before determining the self-consumption metric, the required generator capacity at each site was sized so that total wind energy generation matched total demand over the 2018–2023 period, as expressed in the following equation:

$$G^P = \frac{\sum_{i=1}^{n} E_i^D}{\sum_{i=1}^{n} E_i^{G\_1kW}} \tag{3}$$

where: G^P – generator capacity [kW], $E_i^{G\_1kW}$ – energy generation from normalized 1 kW source, n – integration time, hourly over the years 2018–2023.

This approach aligns with the typical sizing procedures used for small residential renewable energy systems. In such systems, the generation capacity is often selected to closely match the annual energy consumption of the site, optimizing self-consumption and minimizing excess generation that would otherwise be exported to the grid.

2.5. Capture price

For a customer with a dynamic electricity tariff, the capture price [39] of a small wind turbine reflects the savings from using self-generated wind power instead of purchasing electricity from the grid at fluctuating prices. It represents the effective cost avoided when wind generation coincides with higher electricity prices, maximizing economic benefits. When a wind turbine produces power during peak price periods, the capture price is higher, indicating greater savings. Conversely, if generation occurs during low-price periods, the capture price decreases, and savings are reduced. This metric provides insight into the economic value of wind generation under a dynamic tariff system and helps assess its contribution to reducing electricity bills. Additionally, capture price serves as a benchmark for comparing the economic performance of small wind generation against large-scale wind turbines and solar PV. The following formula was used to calculate capture price (CP):

$$CP = \frac{\sum_{i=1}^{n} \left(P_i^{DA} * E_i^{WT}\right)}{\sum_{i=1}^{n} E_i^{WT}} \tag{4}$$

where: P_i^{DA} – is the electricity price on day-ahead market [Euro/kWh] at time step (hour) i, E_i^{WT} – is the energy generated by wind turbine at time step (hour) i [kWh].

2.6. Levelized cost of electricity

To broaden the economic analysis and facilitate comparisons with other technologies, this study adopts the levelized cost of electricity (LCOE) metric. LCOE allows for the comparison of different power generation technologies or the same technology deployed in different locations. As defined in Eq. (5) [40], LCOE is calculated by dividing total lifetime costs by total energy generation, discounted over the project lifetime. Unlike Konstantin [37], this study employs the Weighted Average Cost of Capital (WACC) as the discount rate instead of the real interest rate. WACC accounts for both debt-financed and self-financed investments, ensuring a more comprehensive economic assessment. In the case of a fully self-financed investment, WACC reflects the opportunity cost of capital, representing the returns the funds could have earned elsewhere.

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{5}$$

where: I_0 – investment expenditure [Euro] in year 0, A_t – annual total cost [Euro] per year t, E_t – electricity produced [kWh] in year t, i –discount rate [%], n – economic lifetime of a project [years].

The assumptions concerning the values of individual parameters relevant for the LCOE calculations are presented in Table 2.

Table 1
Values of parameters used in LCOE calculations.

Parameter	Value	Reference
Investment/CAPEX (I_0)	Avg: 6500, min: 2913, max 11605	[41–44]
Annual total cost/OPEX (A_t)	2.5 [%] of I_0	[45]
Project lifetime (n)	20 [years]	[46]
Electricity production (E_t)	Site specific, CF based	*This work*
Discount rate (i)	6 [%]	[47]
Degradation	1.6 [%/year]	[48]

The investment expenditures (CAPEX) are derived from four reports prepared by various institutions including: Pacific Northwest National Laboratory [43], American Wind Energy Associations [44], Centre for Sustainable Systems – University of Michigan [42] and the Danish Energy Agency (referenced through [41]). The annual maintenance cost is assumed to be identical as the one for solar PV systems. The degradation rate is adopted from a work by Staffel and Green [48] which concerned large wind turbines as such studies for small wind turbines are yet unavailable.

Table 2
Self-consumption rates depending on the load profiles, energy sources and location. The last two columns present average (AVG) and standard deviation (STD) among locations.

Load profile	Source	Location														
		Pilsko	Bezek	Karżniczka	Rozewie	Gdynia	Frombork	Kmiecin	Rzeszów	Kołobrzeg	Ustka	Łeba	Gdańsk	Elbląg	AVG	STD
B	**Wind**	34 %	41 %	40 %	51 %	44 %	37 %	43 %	40 %	41 %	47 %	46 %	43 %	43 %	42.3 %	4.1 %
	PV	36 %	37 %	36 %	35 %	36 %	36 %	36 %	38 %	36 %	36 %	35 %	36 %	36 %	36.0 %	0.5 %
C	**Wind**	31 %	40 %	40 %	49 %	43 %	36 %	43 %	40 %	40 %	46 %	46 %	43 %	42 %	41.4 %	4.1 %
	PV	41 %	42 %	41 %	41 %	41 %	41 %	41 %	43 %	41 %	41 %	40 %	41 %	41 %	41.2 %	0.5 %
C11o	**Wind**	33 %	30 %	24 %	40 %	30 %	28 %	25 %	24 %	27 %	33 %	31 %	27 %	32 %	29.7 %	4.1 %
	PV	3 %	4 %	3 %	3 %	3 %	3 %	3 %	4 %	3 %	3 %	3 %	3 %	3 %	3.0 %	0.3 %
C12a	**Wind**	32 %	40 %	40 %	50 %	43 %	37 %	43 %	39 %	41 %	47 %	46 %	43 %	42 %	41.9 %	4.2 %
	PV	38 %	38 %	38 %	38 %	38 %	38 %	38 %	39 %	38 %	38 %	37 %	38 %	38 %	38.0 %	0.4 %
C12b	**Wind**	35 %	41 %	38 %	51 %	43 %	37 %	41 %	38 %	40 %	46 %	45 %	42 %	43 %	41.5 %	4.0 %
	PV	29 %	30 %	29 %	29 %	29 %	29 %	29 %	30 %	29 %	29 %	29 %	29 %	29 %	29.3 %	0.4 %
G11	**Wind**	34 %	41 %	40 %	51 %	44 %	37 %	43 %	39 %	41 %	47 %	46 %	43 %	43 %	42.2 %	4.1 %
	PV	34 %	34 %	34 %	33 %	33 %	34 %	34 %	35 %	34 %	34 %	33 %	34 %	34 %	33.8 %	0.4 %
G12	**Wind**	35 %	42 %	40 %	52 %	44 %	37 %	43 %	40 %	41 %	47 %	46 %	44 %	44 %	42.7 %	4.1 %
	PV	31 %	31 %	31 %	30 %	31 %	31 %	31 %	32 %	31 %	31 %	30 %	31 %	31 %	31.0 %	0.4 %
G12w	**Wind**	34 %	42 %	41 %	52 %	44 %	38 %	44 %	40 %	41 %	47 %	47 %	44 %	44 %	42.9 %	4.1 %
	PV	36 %	37 %	36 %	36 %	36 %	36 %	36 %	38 %	36 %	36 %	35 %	36 %	36 %	36.1 %	0.6 %
G12as	**Wind**	33 %	35 %	32 %	46 %	37 %	34 %	34 %	31 %	36 %	42 %	40 %	35 %	37 %	36.3 %	3.8 %
	PV	20 %	20 %	20 %	20 %	20 %	20 %	20 %	21 %	20 %	20 %	20 %	20 %	20 %	20.1 %	0.3 %

2.7. Solar PV modelling

The PV GIS [49] tool from the Joint Research Centre (JRC) was used to simulate the photovoltaic systems. The SARAH3 database was selected as the source for solar radiation data, ensuring an accurate representation of local conditions. The PV systems were modelled with an inclination angle set to 30° and an azimuth facing south, maximizing solar PV energy generation. Crystalline silicon PV modules were considered for the analysis, with overall system losses, including factors such as shading and temperature, assumed to be 14 %. The PV generation was modelled with an hourly resolution for several sites singled out based on wind conditions that were considered as favourable (CF > 10 %). Originally the installed capacity was set to 1 kW.

3. Results and discussion

This section presents the results of the conducted simulations and analyzes them in the context of existing literature. The findings are examined to highlight key trends, compare them with previous studies, and discuss their implications.

3.1. Potential and generation profiles

The analysis of 173 locations (see map on Fig. 4), shows that wind conditions at 10 m above ground level tend to be highly unfavorable for wind turbines. The mean capacity factor over the period 2018–2023 for all locations is 3.75 % with a standard deviation of 3.6 percentage points. For comparison, this is roughly three times lower than a typical capacity factor for the PV systems under the Central European irradiation conditions [49]. At 156 sites (90 %) the capacity factor is lower than 8 % and at 127 sites it is even less than 5 %. Almost 55 % of all sites are characterized by capacity factor of less than 3 %. Only around 6 % of locations have a capacity factor greater than 10 % and only three exceed 19 %. All these locations that exhibit high-performance of wind turbines are on the Baltic Sea coast, which naturally experiences the most favourable wind conditions. Individual sites inland show CFs in the range of 7–10 %. Notably even sites located close to each other can have very different wind potentials as it is in particular observed in southern Poland, due to the local topography.

However, even the windiest locations experience a high variability and intermittency of wind generation. As shown on Fig. 5, prolonged periods of near-zero or zero generation are common. For example, in Rozewie (Northern Poland) in May 2018 (see Fig. 5 bar plot), the monthly generation was much (70 kWh/kW) lower compared to 2018–2023 mean.

Analysis of daily generation profiles for small wind turbines across different months (Fig. 6) shows that the average site (green line) reaches peak generation around noon to 1 p.m., coinciding with peak output from south-oriented PV systems. This midday peak results from thermal turbulence, where solar heating causes convection currents that enhance wind speeds, particularly at lower altitudes (~10 m) [50]. Additionally, diurnal wind patterns contribute to this effect, as daytime solar heating increases atmospheric mixing, strengthening winds, while nighttime stability reduces wind speeds [51]. Surface roughness and friction

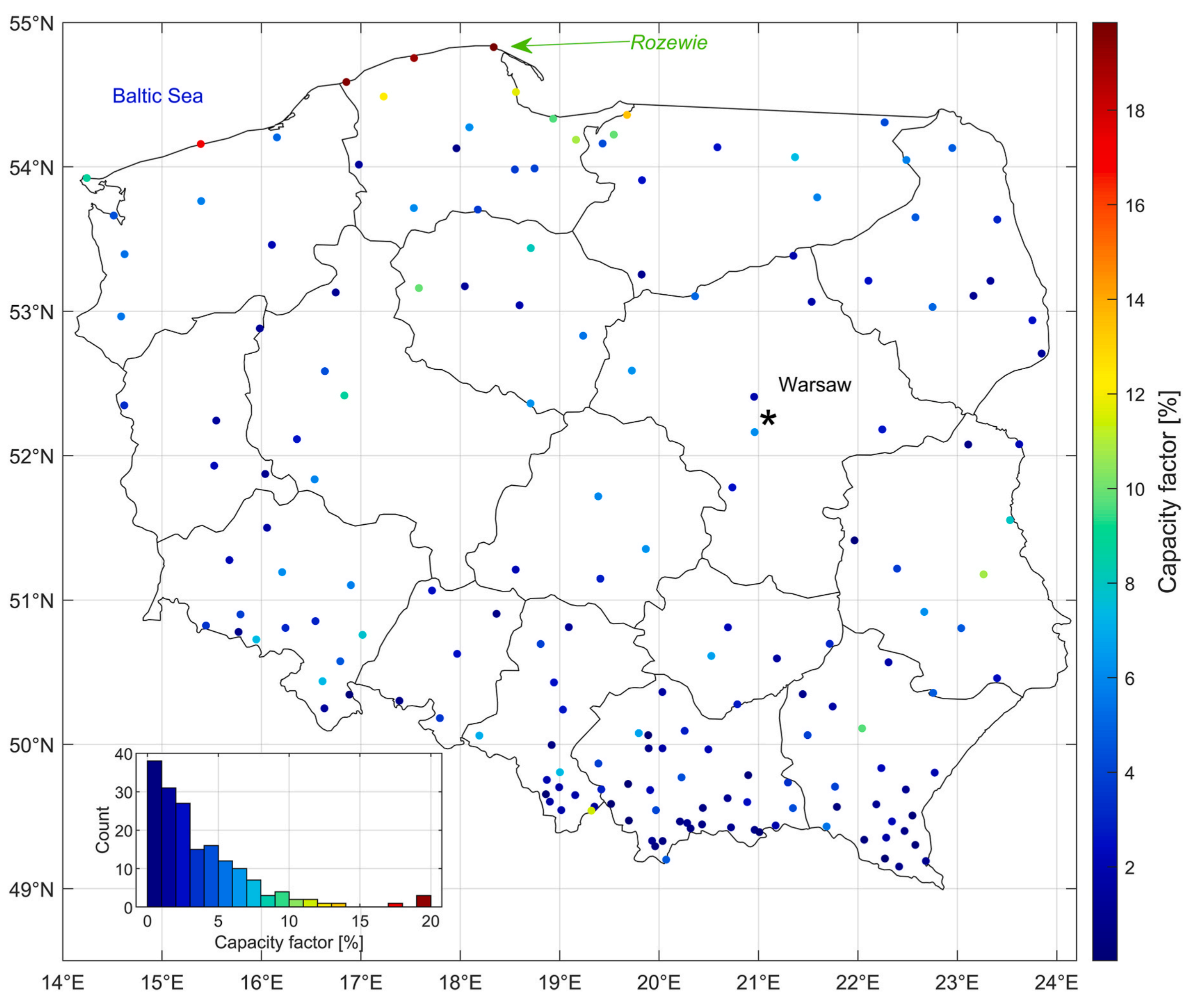

Fig. 4. Averaged multiannual (2018–2023) capacity factors calculated for selected locations for further analysis.

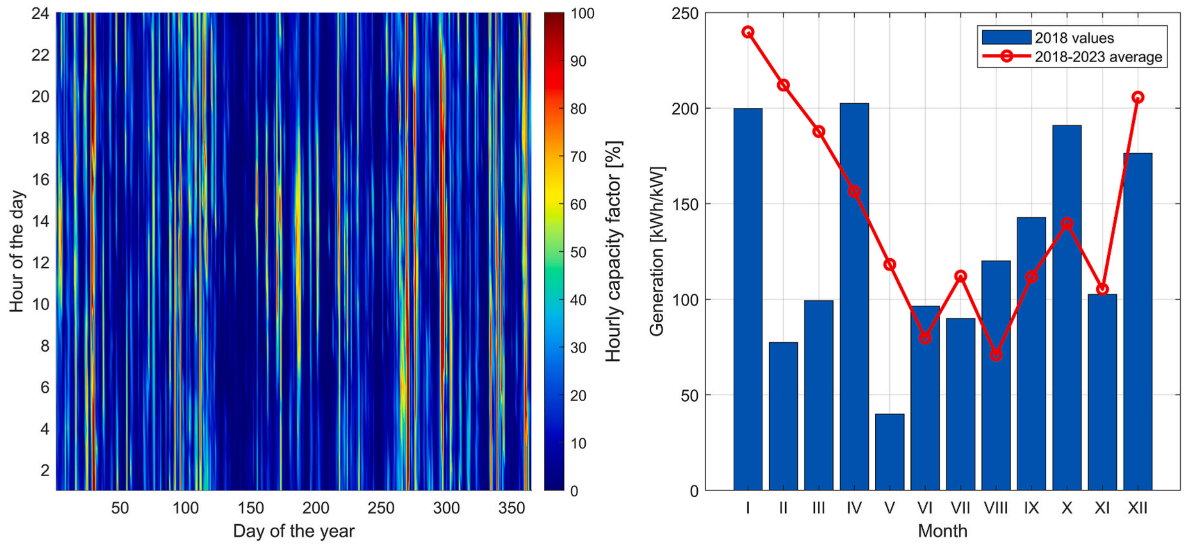

Fig. 5. Simulated capacity factor of small wind turbine located in Rozewie (on Fig. 4 a site indicated by a green arrow) – Northern Poland over the year 2018 with an hourly (left) and monthly (right) temporal resolution.

further influence wind behavior, but daytime thermal turbulence helps overcome these effects, enhancing energy capture. Together, these meteorological factors explain why small wind turbines often generate more power during daylight hours.

In Fig. 6, a specific site in Southern Poland (dotted line) is highlighted due to its distinct daily generation profile. From February to November, its pattern more closely resembles that of large-scale wind turbines, with lower average generation during daytime. This is because the site, located at 1400 m above sea level, experiences wind conditions typical of higher elevations, where diurnal wind fluctuations differ from those at lower altitudes.

Beyond the seasonal and daily variability in small-scale wind turbine generation, the 2018–2023 data reveal interannual fluctuations. Among the 13 stations with a multiannual capacity factor above 10 %, 2019 had the highest wind generation potential with an average capacity factor of 14.75 %, while 2018 had the lowest at 11.23 %. At the individual station level, year-to-year capacity factor variation reached 7.6 percentage points (22.6 % in 2020 vs. 15 % in 2018).

3.2. Self-consumption

As previously discussed, self-consumption refers to the direct use of electricity generated by a renewable energy system [5] on site. A high level of self-consumption typically indicates that the electricity generated is consumed locally at a cost close to the generator's levelized cost of electricity, rather than being subject to market prices or grid tariffs. In an ideal case where self-consumption reaches 100 %, all electricity generated by a given source is used on-site, meaning that this part of local electricity demand is met at the generator's LCOE. If both self-consumption and self-sufficiency (amount of power supplied from own sources) were simultaneously at 100 % and supplied entirely by a single energy source, the entire electricity demand would be covered exclusively at that source's LCOE, without reliance on external electricity markets or the grid.

Conversely, a low level of self-consumption implies that the generator cannot cover a significant portion of the local load, requiring additional electricity from other sources, which may be subject to market price fluctuations and grid tariffs. At the same time, surplus energy from the generator must be managed, either by storing it (which incurs additional costs), selling it—often at lower prices than the retail electricity rate—or simply curtailing excess production, leading to wasted energy and reduced overall economic efficiency. The level of self-consumption depends on several factors, including the generator's capacity, the load profile and, variability of supply and most importantly the temporal relationship between demand and supply.

In this study, nine typical load profiles (Fig. 1A in the Appendix) provided by local Polish distribution system operator [38] were analyzed. These profiles represent demand patterns for different customer types over a whole calendar year. For clarity, Fig. 7a represents only the typical daily load profiles. Using the method outlined in Section 2.4, self-consumption was calculated for all 173 sites. As expected, locations with very low-capacity factor (Fig. 11b) also exhibit low self-consumption rates, as these sites experience only relatively short periods of high wind potential in between prolonged periods of very low generation.

For most systems with a mean capacity factor exceeding 5 %, self-consumption ranges from 20 % to 40 %. In economically promising wind locations (capacity factor >10 %), self-consumption varies between 25 % and nearly 55 % at the windiest sites. A notable exception is the profile indicated by the dark-green line, which shows lower self-consumption rates. This profile represents customers with nighttime-dominant demand patterns (e.g., bakeries). Since small wind turbines in almost all locations peak during the daytime, they are less suitable for customers with primarily nighttime electricity consumption.

As there is very small rationale for investigating the self-consumption for sites with very low capacity factors the subsequent analysis concentrates only on those with the CF greater than 10 %. In this case a comparison is made of the self-consumption rates not only between sites but also between SWT and solar PV systems. Capacities and self-consumptions were calculated again as per Section 2.4. The results obtained are presented in Table 2. The average self-consumption among all load profiles for SWT are 40.1 % whereas for solar PV are 29.8 %. As expected, for the SWT a higher inter-site variability (expressed through STD) in self-consumption can be observed. The lowest self-consumption in case of both sources was observed for a peculiar load C11o, which is typical for devices that use dusk-to-dawn sensors or are programmed based on sunrise and sunset times or agreed-upon hours. On the other hand, profiles like C12a, G12w, and B show higher self-consumption for both wind and solar, indicating that their demand profiles align better with renewable generation patterns. Overall, the results indicate that self-consumption is not just a function of generation capacity, but rather a complex interaction between location, demand profile, and energy management strategies.

Summarizing, the self-consumption values reported above are

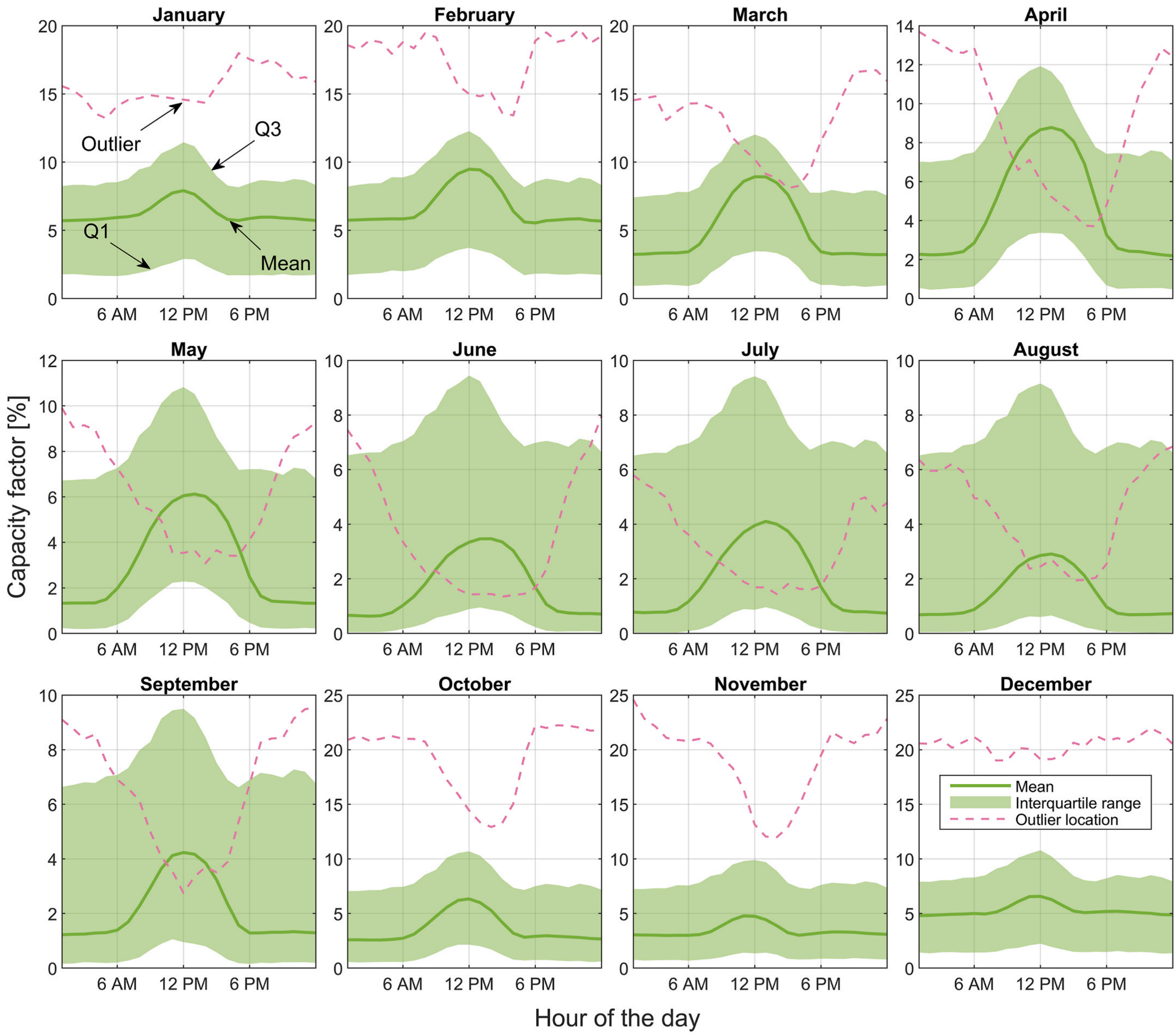

Fig. 6. Variability of typical daily generation profiles among 173 considered locations distinguished by month. Pink dotted line indicates a peculiar location in Southern Poland (49.54N, 19.31E) that exhibits a different profile that is noticeable from February to November.

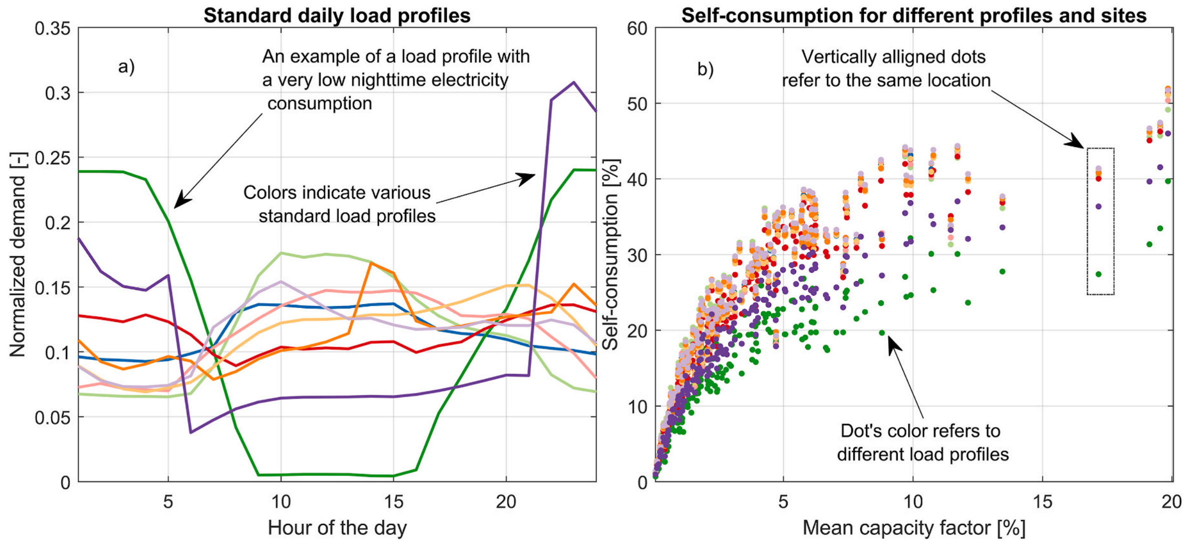

Fig. 7. Investigated standard load profiles (panel a) and a self-consumption as a function of site-specific 2018–2023 mean capacity factor (panel b).

similar to the ones referenced by Ref. [52]. In their review work the PV systems without storage exhibited a self-consumption from 29 % to 38 % in Germany, 41 % in Tokyo (Japan), 20 % in Switzerland, 15 % in Madrid (Spain) or 16 % in Napoli (Italy). These variations result from different supply-demand correlations and the size of the PV systems. Recently [53], reported a self-consumption ratio for a PV system located on a selected household in Southern Poland to be 27.1 %. The analysis conducted here indicates that small-scale wind turbines (with reasonably high-capacity factors) have an opportunity to provide electricity with a significantly higher self-consumption ratio compared to PV systems. Consequently, this higher self-consumption can reduce the dependence on the electrical grid.

3.3. Solar PV vs small-scale wind – temporal matching

As discussed in the Introduction, one key motivation for coupling solar and wind generation or increasing interest in small-scale wind is the temporal complementarity of these two energy sources [54]. This section analyzes complementarity across different time scales, focusing on the ability of a hybrid system to reduce periods of low or zero generation. For this analysis, 13 previously preselected locations (with a capacity factor ≥10 %) were considered. The solar PV generation was simulated using the PV GIS tool as described in Section 2.7, and a 50-50 installed capacity ratio was assumed for the hybrid system.

Fig. 8 and Table 2 present the performance of wind-only, PV-only, and hybrid systems, below estimated mean hourly generation over the analysis period.

- Wind-only system: 0.135 kWh/kW
- PV-only system: 0.119 kWh/kW
- Hybrid system: 0.127 kWh/kW (as expected, an intermediate value)

Although hybridization (at a fixed total installed capacity) slightly reduces overall generation, it significantly decreases power output variability. The coefficient of variation (CV) of the hourly generation time series across all 13 sites was.

- 166 % for wind-only
- 175 % for PV-only
- 122 % for the hybrid system

This demonstrates that a wind-PV hybrid system helps stabilize generation, reducing extreme fluctuations in power output.

Analyzing the daily generation potential (Fig. 8) reveals that hybridization reduces the number of outliers, particularly days with exceptionally high generation. Additionally, the mean daily generation of hybrid systems exceeds that of wind-only systems, though the extent of this effect varies by location (Table 3). Most importantly, the hybridization reduced the number of very low-generation days (energy droughts) on average 4-times in case of wind system and 2.4-times in case of solar PV.

Fig. 9 presents site-specific results for Rozewie (Northern Poland), showing typical daily generation patterns across different months. As before, the horizontal axis represents the hour of the day, while the vertical axis displays power generation in kWh per kW of installed capacity. As previously discussed, (Fig. 6), the wind generation peak often coincides with PV peak generation, particularly during months with lower wind potential. The interquartile ranges for all three generation sources are included to illustrate variability. A key observation is that November appears to be the most challenging month—low PV generation is not sufficiently compensated by higher wind output, highlighting a potential seasonal gap in hybrid system performance.

The results indicate that PV and wind exhibit both seasonal and daily complementarity. The daily complementarity arises from potential wind generation during nighttime, despite overlapping peak generation around midday. Seasonally, PV dominates in summer, while wind ensures a more reliable supply in winter.

Additionally, PV generates power only during daylight hours, whereas wind provides a more continuous output, helping to mitigate intermittency (as shown by the time series statistical parameters in Table 2). The hybrid system effectively smooths fluctuations, offering a more stable generation profile year-round. This underscores the benefits of integrating both energy sources to enhance energy security and reduce reliance on storage or grid support. However, these findings reflect a purely energy-based perspective, as the cost of energy from individual sources is not considered in this analysis.

3.4. Levelized cost of electricity from small wind turbines

As mentioned earlier, LCOE is a key metric for comparing energy sources, both across different technologies and within the same technology deployed in different locations with varying weather conditions. In this study, LCOE was calculated for wind turbines at 173 sites across Poland, while being neutral to the site-specific capacity factors, resulting in a wide range of LCOE values.

For an optimistic scenario with a low investment cost (2913 €/kW,

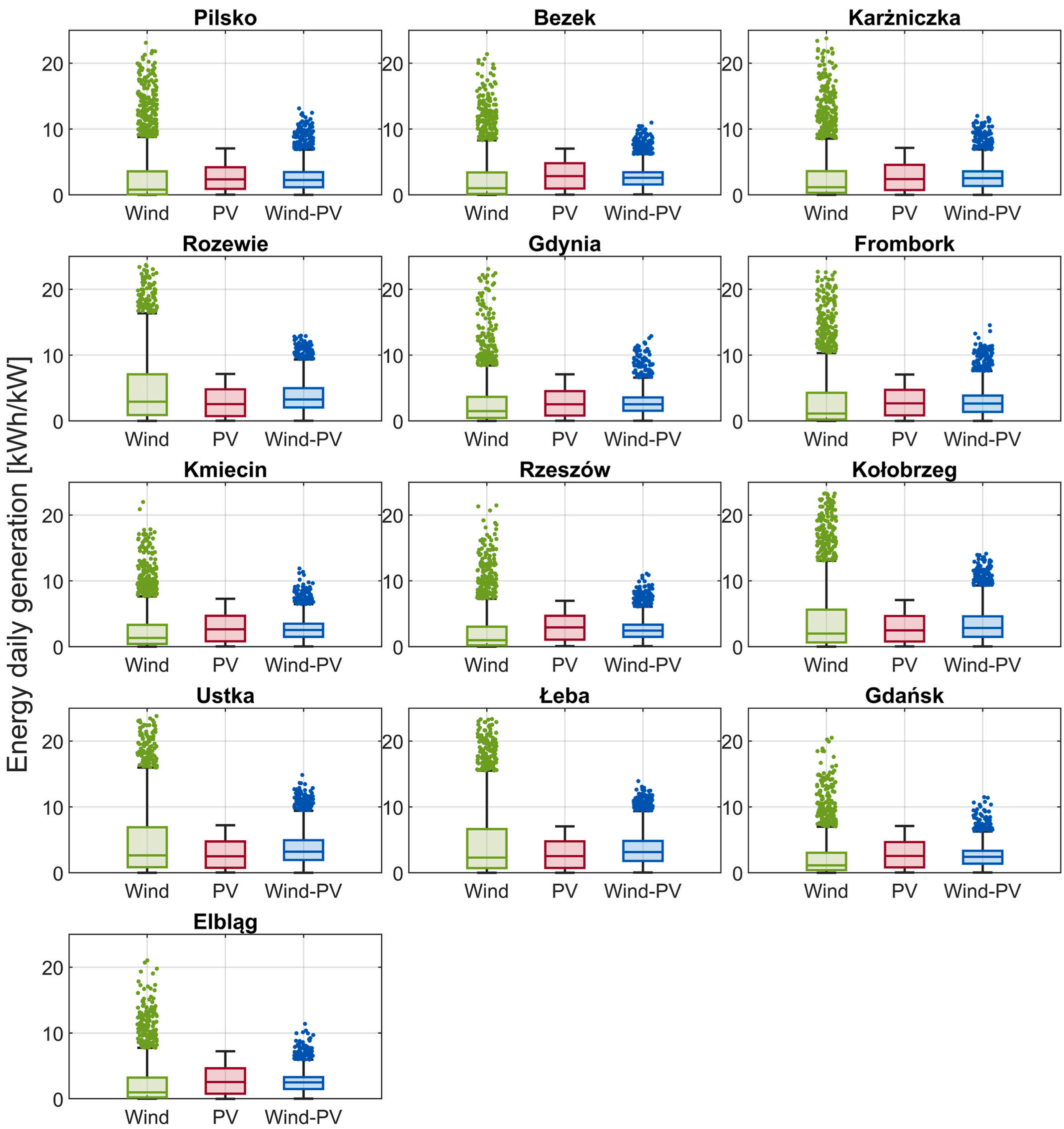

Fig. 8. Box-plots of daily wind, PV and hybrid (wind-PV) generation across 13 locations with wind multiannual capacity factor greater than 10 %. Hybrid system has a 50-50 ratio of PV-wind capacity installed.

Table 1), LCOE ranges from 0.23 €/kWh to as high as 344 €/kWh. The lower end is comparable to Poland's average residential electricity price (0.21 €/kWh [56]). However, when assuming a higher investment cost (6500 €/kW), even the best-performing sites with capacity factors close to 20 % (3 sites) exhibit LCOE values above 0.51 €/kWh, exceeding the highest electricity prices in Europe (Germany, 0.39 €/kWh in early 2024 [56]).

As shown in Fig. 10, only sites with a capacity factor above 10 % can potentially achieve an LCOE below 1 €/kWh, which is still three times higher than the EU average electricity price (0.29 €/kWh in late 2024). Given these findings, only sites with a capacity factor of at least 15 %, combined with low investment costs (minimum CAPEX from Table 1) could achieve competitiveness with average residential electricity prices.

In summary, without a significant reduction in investment costs—similar to the price declines observed in the solar PV sector—small-scale wind turbines will likely remain a niche solution, economically viable only under specific conditions.

Table 3
Basic statistical parameters of daily values presented on Fig. 8 followed up by quantification of days denoted as "drought days" where generation is less than 20 % of multiannual daily generation as per [55].

Parameter	Mean (μ) [kWh/kW]			STD [kWh/kW]			Coefficient of variation			Drought days (<0.2 μ)		
Loc./Source	W	PV	W-PV	W	PV	W-PV	W	PV	W-PV	W	PV	W-PV
Pilsko	2.8	2.7	2.7	4.2	1.9	2.2	154 %	71 %	81 %	44 %	15 %	12 %
Bezek	2.6	3.0	2.8	3.6	2.0	1.8	141 %	68 %	64 %	38 %	17 %	8 %
Karżniczka	2.9	2.8	2.8	4.1	2.1	2.0	141 %	76 %	72 %	34 %	21 %	9 %
Rozewie	4.8	2.9	3.8	5.1	2.2	2.6	107 %	76 %	67 %	26 %	21 %	8 %
Gdynia	2.8	2.8	2.8	3.6	2.1	1.9	128 %	75 %	66 %	28 %	21 %	7 %
Frombork	3.2	2.9	3.1	4.5	2.1	2.4	140 %	73 %	77 %	39 %	20 %	12 %
Kmiecin	2.6	2.9	2.7	3.3	2.1	1.7	126 %	73 %	64 %	28 %	19 %	8 %
Rzeszów	2.3	3.0	2.7	3.3	1.9	1.7	139 %	66 %	63 %	35 %	14 %	6 %
Kołobrzeg	4.1	2.8	3.5	5.0	2.1	2.7	122 %	74 %	78 %	29 %	20 %	11 %
Ustka	4.7	2.8	3.8	5.2	2.1	2.6	110 %	75 %	69 %	26 %	21 %	8 %
Łeba	4.6	2.8	3.7	5.3	2.2	2.7	116 %	76 %	71 %	30 %	22 %	8 %
Gdańsk	2.3	2.8	2.6	3.0	2.1	1.7	130 %	73 %	64 %	28 %	19 %	7 %
Elbląg	2.4	2.8	2.6	3.2	2.1	1.6	136 %	74 %	61 %	35 %	20 %	6 %

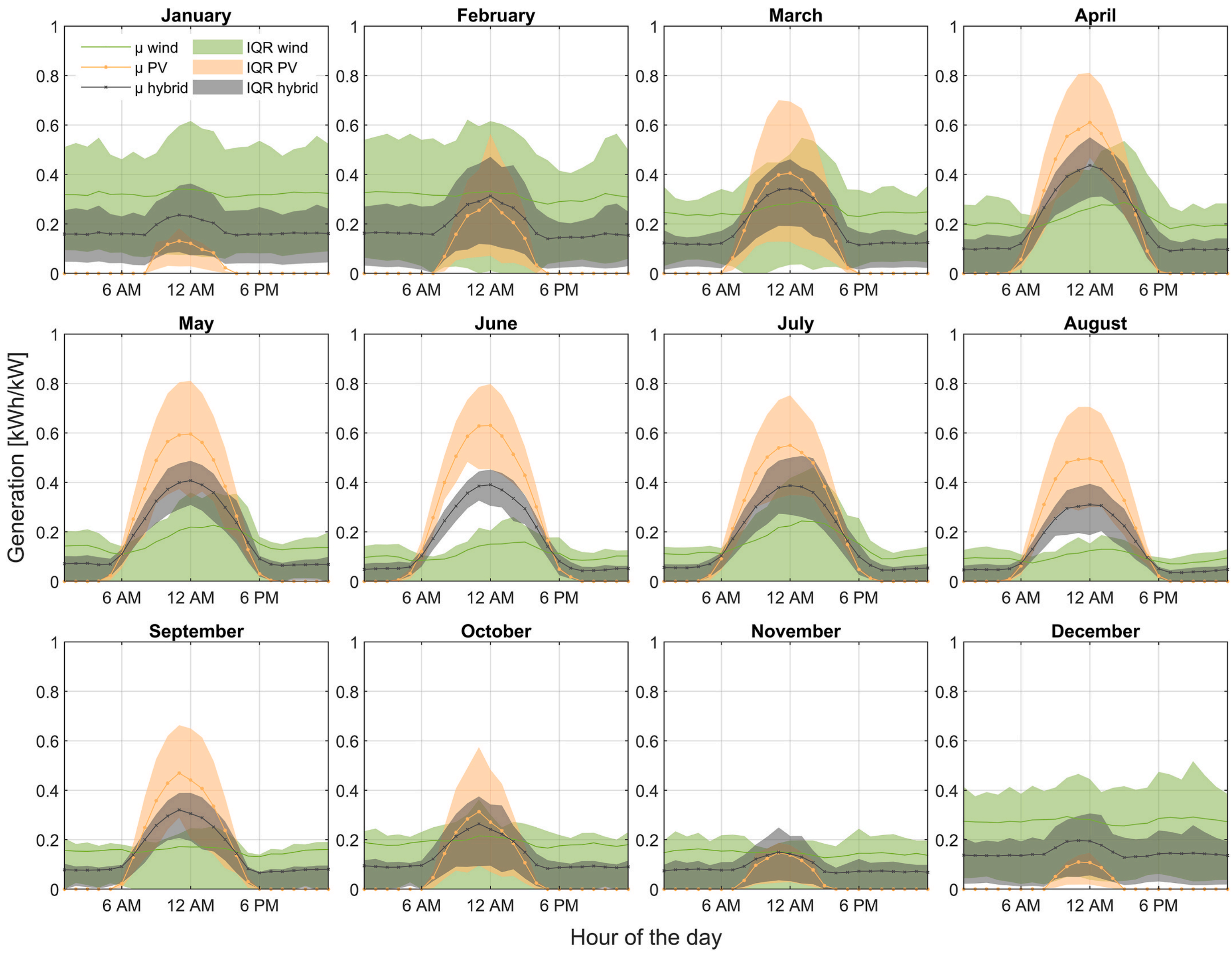

Fig. 9. Wind, solar PV, solar PV – wind operation within each month indicates a very little of potential complementarity between these two energy sources. Results for site: Rozewie (northern Poland).

3.5. Capture price

Although the trajectory of wind turbines investment costs remains uncertain their future financial performance should be evaluated within the context of the power system. The electricity prices paid by customers are an outcome of an intricate interplay between the demand and supply where the latter is becoming more and more variable due to the increasing share of variable renewable generation as well as growing political tensions (e.g. natural gas supply). In this context the day-ahead electricity market plays an increasingly important role in the energy

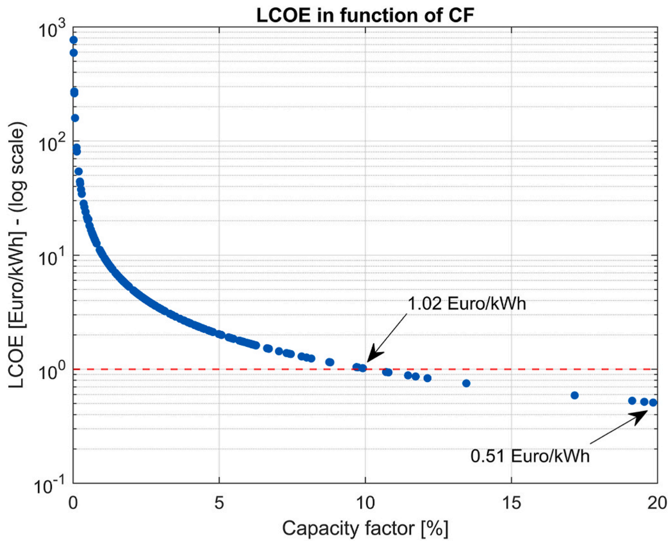

Fig. 10. Levelized cost of electricity calculated for an investment cost of 6.5 kEuro/kW for each one of the 173 sites. The figure shows a relationship between site (dot) multiannual mean capacity factor and the LCOE.

sector, allowing for short-term buying and selling of electricity based on forecasted demand and generation for the following day. This market mechanism helps balance supply and demand efficiently, but it also exposes electricity consumers to greater price volatility. For consumers on dynamic electricity tariffs, which adjust prices based on real-time market conditions, this can lead to fluctuations in electricity costs throughout the day. When demand spikes or renewable energy generation suddenly drops, day-ahead market prices can surge, directly affecting consumers with variable rates. As consumers adopt these tariffs, they are becoming exposed to market volatility, requiring greater attention to usage patterns and time-of-day pricing to manage costs effectively.

Over the past few years (2018–2024[1]), electricity prices in Poland have undergone significant changes. Prices (Fig. 11a) remained relatively stable from 2018 to 2020, supported by a firm and secure electricity supply from conventional generators. However, prices became increasingly volatile after the beginning of Covid in 2020 and the Russian invasion of Ukraine in 2022, both of which disrupted global supply chains. On top of that, the installed capacity in solar PV has experienced a massive increase from a modest 4 GW in 2020 to almost 18 GW in Q1 of 2024 [57]. This rapid expansion in solar capacity has further driven variability in energy prices, even leading to the first instances of negative electricity prices in 2023 and 2024 (in particular).

The variation of electricity prices in Poland on day-ahead market is shown in Fig. 11a. The extending tails (outliers) and the shifting distribution of electricity prices are expected phenomena in an energy system with increasing non-dispatchable sources, such as wind and solar power. These sources generate electricity based on weather conditions, which are inherently variable. As a result, periods of both excess and scarcity of electricity generation become more frequent. During times of high renewable output, prices can drop significantly, sometimes even falling into negative territory, while during low generation periods, prices can spike due to the increased reliance on more expensive dispatchable sources or even the need to import electricity. The above is supported by Fig. 11b which shows the relationship between the electricity generation from large scale (horizontal axis) and small scale (vertical axis) wind turbines. Each dot represents 1 h during the year 2023 and its colour refers to the day-ahead electricity price, with dark red indicating prices above 200 Euros/MWh and dark blue below 0 Euros/MWh.

Overall, an expected and clear tendency is visible: on average, higher wind generation leads to lower electricity prices on the day-ahead market. Although at the same value of large-scale wind generation significant price variation can be observed this is most likely driven by the national electricity demand and other factors like generators availability, which is outside the scope of this work. What is, however, more important is that the generation of small- and large-scale wind turbines is highly correlated (the Pearson Coefficient of Correlation = 0.85). As a result, during periods of high wind generation, electricity prices on the day-ahead market will likely be lower due to the surplus in supply. This means that small wind turbines may not be as profitable for owners using dynamic pricing tariffs, as the value of the electricity generated is reduced during these times. Given the relatively low-capacity factors of small-scale wind turbines, combined with their higher investment cost (Euro/kW) compared to solar PV, they are likely to be unprofitable unless the goal is to maximize energy self-sufficiency and reduce the reliance on the national grid.

Considering the above-described large exposure of investment in small wind turbines to other technologies and the overall energy system and associated with it energy market this study dives additionally into the concept of capture price (see Section 2.5). The analysis was conducted over the period 2018–2023 based on the following.

- large-scale wind generation (based on the data reported to ENTSO-E),
- small-scale wind turbines (by generating averaged hourly capacity factor based on locations with mean multiannual capacity factor greater than 10 %),
- and the averaged capacity factor of PV systems located at the same sites as the small-scale wind turbines.

The mean monthly capture prices for each energy source are presented in Fig. 12. As expected, lower capture prices were observed between 2018 and 2020, with a noticeable increase starting in June 2021 across all technologies. Large-scale wind performed particularly poorly in 2020, with an average capture price of 44.4 €/MWh. However, this surged in 2022, reaching an annual average of 149.9 €/MWh and peaking at 264 €/MWh in August 2022. Across small wind, PV, and large wind, capture prices exhibited an overall upward trend from 2018 to 2023, particularly peaking in 2021 and 2022.

Among the technologies.

- Small wind turbines displayed the highest volatility, with sharp price fluctuations.
- PV capture prices were highest during summer months, reflecting peak solar production.
- Large-scale wind was the most stable, but still followed the general trend of increasing capture prices.

By 2023, capture prices stabilized or slightly declined, particularly in the second half of the year. In 2018, solar PV had a capture price over 10 €/MWh higher than both small and large wind. This price gap narrowed to 7.6 €/MWh in 2019 and 5.7 €/MWh in 2020, before widening again to 11.5 €/MWh in 2021. In 2022, the mean capture prices across all technologies converged, fluctuating between 141 and 150 €/MWh, with small wind showing the lowest value.

At a monthly timescale, greater differences emerged. For example, in December 2022, solar PV's capture price was 52 €/MWh higher than that of large-scale wind, highlighting significant seasonal variability in market valuation.

Based on the 2018–2023 analysis, a key finding is that small wind

[1] The revised version of the manuscript now includes the complete set of electricity prices for 2024. However, the wind related analysis does not cover this year as the processed and validated data from wind stations was not yet available at the time of writing. Prices for 2024 are shown to shed more light on price variability.

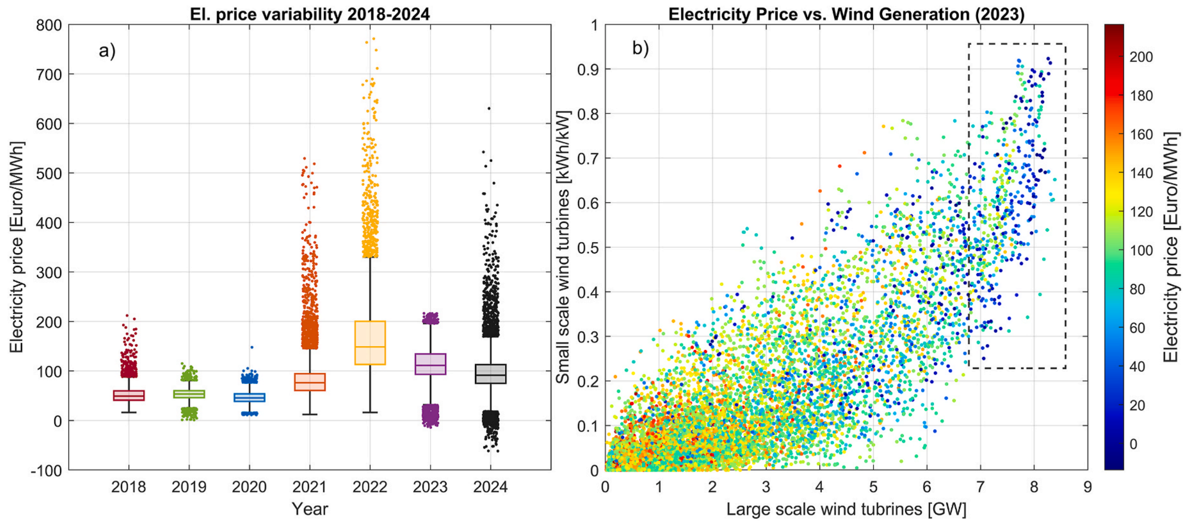

Fig. 11. Panel a) day-ahead electricity prices over 8 consecutive years, panel b) hourly electricity price in a function of large scale and small-scale wind turbines generation over the year 2023. A strong correlation (0.845) between wind sources indicates higher potential for cannibalization effect in case of investment in small wind turbines.

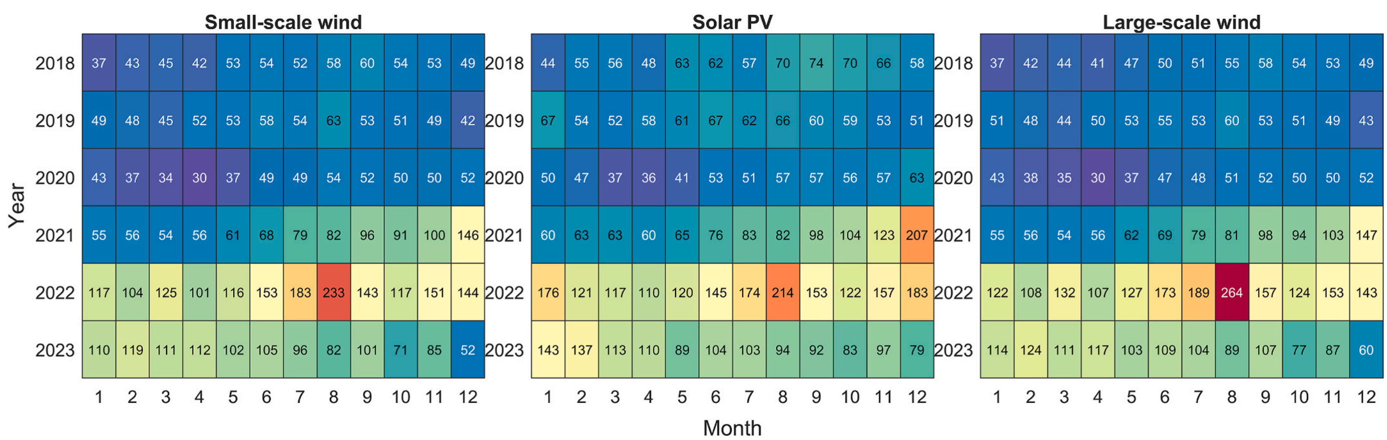

Fig. 12. Average monthly capture price [Euro/MWh] between various technologies indicating potential revenues from participating in the day-ahead market or savings through avoided purchases on the market thanks to consuming electricity from own generator.

consistently had lower capture prices than PV, indicating that electricity from small wind turbines is typically generated during periods of lower market prices. In contrast, PV benefits from higher capture prices, as its generation aligns with peak solar hours when electricity prices tend to be higher.

This suggests that small wind owners are more likely to generate power when prices are low but the system owner may need to purchase electricity from the grid at higher prices, potentially leading to unfavorable economic outcomes unless carefully managed. These findings highlight the importance of strategically integrating small wind with other energy sources or storage solutions to mitigate exposure to market price fluctuations. When combined with the high LCOE values presented in Section 3.4, this underscores the economic challenges and uncertainties associated with investing in small wind turbines. Without significant cost reductions or market incentives, the financial viability of small wind remains highly uncertain.

3.6. Discussion

This section dives into the two most important parameters when it comes to the assessment of economic viability of investment in wind turbines namely the self-consumption ratio and the levelized cost of electricity. The two subsequent subsections discuss them in the light of the available literature whereas the third subsection outlines the potential future research directions that could evolve outside this work and also complement its shortcomings.

3.6.1. Self-consumption, comparison with other studies

Self-consumption is a key metric indicating how much of the electricity generated by a given source is consumed onsite. Higher self-consumption values reflect a better supply-demand match. In an ideal scenario where, self-consumption reaches 100 % and generation perfectly matches demand the cost of electricity would be equal to the generation cost at the source level. In this study, self-consumption levels were calculated across sites with varying capacity factors and different load profiles. As noted in Section 3.2, sites with capacity factors exceeding 10 % exhibited self-consumption rates between 25 % and 55 %, depending on the load profile.

These findings align well with results from previous studies: Kästel and Gilroy-Scott [58] modelled demand profiles and wind generation at six sites in the United Kingdom, reporting self-sufficiency levels ranging from 46.7 % to 67.8 %, depending on site conditions and load profiles. Their study concluded that lower generation variability leads to higher self-consumption ratios. Bayod-Rujula et al. [59] analyzed self-consumption in Spain (Aragon region) and reported a 51 % self-consumption ratio. However, this study relied on downscaled large-scale wind generation time series to fit residential demand, which may not fully reflect small wind turbine behavior. Given these comparisons, the self-consumption results in this study align well with values reported in the literature, reinforcing the reliability of the findings.

3.6.2. LCOE comparison with other studies

The estimated cost of energy (LCOE) from small wind turbines (SWTs) depends on multiple factors, with local wind conditions and investment costs being the dominant ones. This analysis shows that a site with a capacity factor (CF) of 20 % yields an LCOE of approximately 0.223 €/kWh, assuming a capital expenditure (CAPEX) of 2903 €/kW. This suggests that SWTs could be economically attractive, given that the average residential electricity price in the European Union is around 0.29 €/kWh.

For comparison, small-scale rooftop PV, a well-established technology, exhibits significantly lower LCOE values. A Fraunhofer Institute report [60] estimates the LCOE for rooftop PV to range between 0.06 and 0.14 €/kWh, corresponding to CFs between 10.7 % and 14.6 %, depending on location in Germany. This comparison highlights that even under favourable wind conditions (CF $\approx$ 20 %), SWTs still perform worse than PV in terms of energy cost.

When comparing the LCOE values obtained in this study with those reported in the literature, the following observations emerge. In Poland: Zalewska et al. [30] estimated the LCOE for a 12 kW wind turbine installed at a 15-m mast with a CAPEX of 3166 €/kW and a CF of 25.4 % (based on 2014–2018 data). The resulting LCOE was 0.16 €/kWh for coastal sites and 0.71 €/kWh for less favourable wind locations. A report by Instrat [41] assumed an annual productivity of 1402 kWh/kW (CF = 16 %), an investment cost of 5728 €/kW, and a discount rate of 3 %, yielding an LCOE of 0.323 €/kWh. In Nigeria, Caribbean Islands, Ireland and Iraq: A study [61] analyzed a 20 kW wind turbine installed at a 36.6-m mast across six sites with CFs ranging from 1.3 % to 73 %, assuming an investment cost of 2550 $/kW. The reported LCOE ranged from 0.045 $/kWh to 2.6 $/kWh, depending on site-specific wind conditions. In our analysis, a site with CF $\approx$ 1.3 % resulted in an LCOE of 3.54 €/kWh (for the lowest investment cost scenario), highlighting the impact of low wind availability. A study [62] investigated 20 kW wind turbines at a hub height of 30 m, assuming CAPEX values of 1775 $/kW for systems $\geq$20 kW and 2600 $/kW for systems <20 kW. The LCOE was 0.089 $/kWh and 0.108 $/kWh for sites with CFs of 21 % and 17 %, respectively. A study [63] analyzed 2.4 kW SWTs installed at rural (CF = 21.3 %) and urban (CF = 6.4 %) sites, assuming an investment cost of 6050 €/kW. The resulting LCOE was 0.36 €/kWh for the rural site and 1.2 €/kWh for the urban site, emphasizing the strong dependence of LCOE on wind conditions. Notably lower cost of energy were observed in Iraq [18] for two sites with CFs of 16.9 % and 18.1 % which were in a rage of 0.038–0.057 Euro/kWh.

The reviewed literature demonstrates significant variability in LCOE estimates for SWTs due to differences in investment costs, turbine size, hub height, discount rates, and assumed operational lifetimes. A key finding is that capacity factor, dictated by local wind conditions, remains the primary determinant of LCOE. The LCOE values obtained in this study align with the upper range of literature estimates, primarily due to more conservative investment cost assumptions and lower capacity factors. These results reinforce the notion that, while SWTs can be viable in high-wind regions, their economic competitiveness remains challenging compared to solar PV.

3.6.3. Future considerations

The results presented in this work so far have indicated a high temporal and most importantly spatial variability of energy generation potential from small wind turbines. The range of estimated capacity factors as well as resulting values of the LCOEs indicate that the economical viability assessment is not a straightforward process. Furthermore, the generation from SWT coincides with the peak generation from solar PV on a daily time-scale, this is however location dependent and might significantly vary as recently shown in a study for the continental USA [64]. However, both sources complement each other on a seasonal basis showing that the hybridization has a potential to reduce the frequency and occurrence of low-generation events. The SWT turbines hourly power output strongly correlates with the generation of large-scale onshore wind turbines. This implies that with the continuing trend of increasing installed capacity of the later ones the SWT capture price will further decrease. Considering the high investment cost of SWT it might turn to be more beneficial to rely on dynamic tariffs and simply use available and cheaper electricity from large-scale turbines. This issue requires a further analysis that should also take into account the fact that small prosumer systems might reduce the demand on the expansion of the transmission infrastructure.

Furthermore, the future research should explore the performance of different wind turbine types, investigate hybrid systems combining wind, PV, and battery storage, and conduct comprehensive economic analyses for small wind systems, including inverter and system losses, to improve accuracy and applicability. When it comes to the hybridization a promising area that should be explored is a complementarity of solar PV-SWT systems where the solar PV azimuth is optimized in such a way that peak generation from both sources does not coincide with each other.

4. Conclusions

This analysis provides key insights into the performance of small-scale wind turbines (SWTs) at 10 m above ground level in Poland. The findings highlight several challenges that limit their economic viability.

- Unfavorable wind conditions: The average capacity factor across 173 locations is only 3.7 %, significantly lower than that of PV systems in Central Europe. While daytime generation benefits from thermal turbulence and diurnal wind patterns, overall capacity factors remain too low to ensure profitability, especially for consumers on dynamic electricity tariffs.
- Market impact & cannibalization: Small wind generation correlates strongly with large-scale wind turbines, leading to a cannibalization effect—high wind output lowers day-ahead market prices, reducing financial returns for small wind owners.
- Economic viability & investment costs: Compared to PV, SWTs face higher investment costs and lower capacity factors, making them less attractive economically unless self-sufficiency is the primary goal.
- Self-consumption potential: Sites with capacity factors above 10 % can achieve self-consumption rates of 25–50 %, outperforming typical PV systems. Promising locations can reach 40–60 %, but their limited availability restricts widespread adoption.
- Hybrid wind-solar performance: Hybrid systems show a modest improvement in capacity factor and a reduction in zero-generation days, highlighting potential complementarity between wind and solar.
- Capture price trends & volatility: Between 2018 and 2023, capture prices increased across all technologies but exhibited significant volatility, particularly for small wind and PV during peak renewable generation periods.

The findings strongly suggest that small-scale wind turbines at 10 m above ground level in Poland are not economically feasible under current conditions. With almost one-third of analyzed locations having capacity factors below 3 %, the potential for consistent, reliable generation is limited. Additionally, the correlation with large-scale wind generation exacerbates price cannibalization, further reducing economic returns—particularly for consumers on dynamic tariffs. Despite some self-consumption potential, low-capacity factors and higher investment costs compared to PV make small wind an unattractive investment. Unless technological advancements or significant cost reductions occur, small-scale wind turbines are unlikely to become a viable economic solution in Poland.

CRediT authorship contribution statement

Jakub Jurasz: Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bogdan Bochenek:** Writing – original draft, Software, Resources, Formal analysis, Data curation. **Joanna Wieczorek:** Writing – original draft. **Adam Jaczewski:** Writing – original draft. **Alexander Kies:** Writing – review & editing, Investigation. **Mariusz Figurski:** Writing – review & editing, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT-4o in order to improve the readability of the individual section of the manuscript to more clearly convey the main message. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 4
Location and wind energy potential for meteorological stations considered in this work.

#	Station ID	Name	WGS84_Latt [°]	WGS84_Long [°]	Altitude [m a.s.l.]	Mean annual generation [kWh/kW]	Capacity factor [%]
1	249180010	PSZCZYNA	49.996	18.919	270	45.7	0.5 %
2	249180160	BRENNA	49.754	18.871	350	164.3	1.9 %
3	249180210	SZCZYRK	49.703	18.995	600	137.9	1.6 %
4	249180230	WISŁA	49.655	18.861	430	1.2	0.0 %
5	249180260	ISTEBNA-KUBALONKA	49.604	18.901	780	138.5	1.6 %
6	249190030	LIBERTÓW	49.973	19.895	318	66.6	0.8 %
7	249190090	INWAŁD	49.867	19.389	350	344.4	3.9 %
8	249190190	MAKÓW PODHALAŃSKI	49.726	19.688	361	10.1	0.1 %
9	249190240	LACHOWICE KRALE	49.688	19.418	616	264.1	3.0 %
10	249190280	KRZECZÓW	49.684	19.910	548	188.0	2.1 %
11	249190390	MARKOWE SZCZAWINY	49.588	19.516	1193	3.3	0.0 %
12	249190440	KORBIELÓW	49.569	19.348	650	103.0	1.2 %
13	249190480	LALIKI	49.545	19.016	680	153.6	1.8 %
14	249190520	OBIDOWA	49.544	19.969	805	363.4	4.1 %
15	249190530	PILSKO	49.541	19.318	1278	1004.4	11.5 %
16	249190560	JABŁONKA	49.472	19.696	614	5.6	0.1 %
17	249190640	NOWE BYSTRE	49.332	19.929	870	95.9	1.1 %
18	249190890	RADZIECHOWY	49.649	19.156	395	146.2	1.7 %
19	249200020	ŁAZY	49.965	20.495	245	180.9	2.1 %
20	249200110	JODŁOWNIK	49.771	20.225	384	387.8	4.4 %
21	249200130	JASTRZĘBIA	49.786	20.896	288	25.8	0.3 %
22	249200240	PTASZKOWA	49.600	20.887	520	210.0	2.4 %
23	249200260	ŁĄCKO	49.560	20.439	366	42.4	0.5 %
24	249200340	DĘBNO	49.466	20.209	536	49.3	0.6 %
25	249200360	MIZERNA	49.455	20.282	570	84.9	1.0 %
26	249200370	KROŚCIENKO	49.446	20.432	435	48.8	0.6 %
27	249200420	NIEDZICA	49.418	20.316	534	37.0	0.4 %
28	249200470	KRYNICA	49.408	20.961	582	60.7	0.7 %
29	249200910	MORSKIE OKO	49.201	20.071	1400	413.1	4.7 %
30	249200920	PIWNICZNA	49.425	20.723	380	79.8	0.9 %
31	249200930	PORONIN	49.330	20.035	776	43.8	0.5 %
32	249201010	SIERCZA	49.973	20.034	336	148.9	1.7 %
33	249210070	BIECZ-GRUDNA	49.735	21.296	285	297.3	3.4 %
34	249210150	IWONICZ-ZDRÓJ	49.567	21.788	425	31.3	0.4 %
35	249210170	BARTNE	49.559	21.346	540	378.4	4.3 %

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Table 4 (*continued*)

#	Station ID	Name	WGS84_Latt [°]	WGS84_Long [°]	Altitude [m a.s.l.]	Mean annual generation [kWh/kW]	Capacity factor [%]
36	249210230	WYSOWA	49.438	21.173	519	163.0	1.9 %
37	249210240	BARWINEK	49.431	21.685	465	472.0	5.4 %
38	249210260	TYLICZ	49.392	21.009	585	3.4	0.0 %
39	249220040	DYNÓW	49.835	22.235	249	193.8	2.2 %
40	249220060	BIRCZA	49.687	22.481	324	88.7	1.0 %
41	249220080	SANOK-TREPCZA	49.585	22.185	307	95.0	1.1 %
42	249220120	LESZCZOWATE	49.507	22.548	486	16.4	0.2 %
43	249220150	SOLINA-JAWOR	49.400	22.468	459	59.8	0.7 %
44	249220170	BALIGRÓD-MCHAWA	49.354	22.284	430	150.1	1.7 %
45	249220180	KOMAŃCZA	49.339	22.063	478	33.7	0.4 %
46	249220220	POLANA	49.303	22.577	458	21.0	0.2 %
47	249220240	ŻUBRACZE	49.209	22.272	623	1.5	0.0 %
48	249220280	STUPOSIANY	49.192	22.683	547	80.3	0.9 %
49	249220290	ROZTOKI GÓRNE	49.153	22.414	700	63.5	0.7 %
50	250150170	JAKUSZYCE	50.823	15.442	855	307.1	3.5 %
51	250150220	KARPACZ	50.779	15.769	567	65.2	0.7 %
52	250150250	PAPROTKI	50.727	15.948	543	652.7	7.4 %
53	250160090	PSZENNO	50.854	16.543	223	260.9	3.0 %
54	250160130	SZCZAWNO-ZDRÓJ	50.807	16.241	431	273.5	3.1 %
55	250160360	TARNÓW	50.575	16.793	296	405.2	4.6 %
56	250160520	LĄDEK-ZDRÓJ	50.345	16.885	461	20.1	0.2 %
57	250160590	DŁUGOPOLE-ZDRÓJ	50.250	16.633	364	112.1	1.3 %
58	250170110	DOBROGOSZCZ	50.759	17.017	175	685.1	7.8 %
59	250170330	GŁUCHOŁAZY	50.302	17.387	348	56.6	0.6 %
60	250170390	GŁUBCZYCE	50.182	17.795	290	320.4	3.7 %
61	250180030	STARE OLESNO	50.905	18.364	224	58.3	0.7 %
62	250180270	ŚWIERKLANIEC	50.429	18.943	285	213.0	2.4 %
63	250180580	DRONIOWICE	50.695	18.808	270	346.2	4.0 %
64	250190470	KRAKÓW-WOLA JUSTOWSKA	50.064	19.890	204	11.0	0.1 %
65	250200130	KLISZÓW	50.613	20.525	206	581.5	6.6 %
66	250200210	MIECHÓW	50.363	20.033	299	130.7	1.5 %
67	250200230	BORUSOWA	50.278	20.787	171	244.0	2.8 %
68	250200280	IGOŁOMIA	50.094	20.256	202	247.1	2.8 %
69	250210130	STASZÓW	50.595	21.185	219	126.4	1.4 %
70	250210180	CHORZELÓW	50.348	21.444	170	70.2	0.8 %
71	250210220	KOLBUSZOWA	50.262	21.746	200	143.6	1.6 %
72	250210240	ZAWADA	50.064	21.493	200	343.6	3.9 %
73	250220030	WYSOKIE	50.918	22.667	260	540.5	6.2 %
74	250220120	JAROCIN	50.569	22.307	183	145.1	1.7 %
75	250220140	TARNOGRÓD	50.357	22.757	237	419.1	4.8 %
76	250230020	NIELISZ	50.805	23.039	200	412.3	4.7 %
77	250230070	TOMASZÓW LUBELSKI	50.458	23.399	270	199.8	2.3 %
78	251150180	TOMASZÓW BOLESŁAWIECKI	51.276	15.678	186	180.3	2.1 %
79	251160150	POLKOWICE DOLNE	51.501	16.056	160	132.1	1.5 %
80	251160320	RADZYŃ	51.873	16.038	60	87.0	1.0 %
81	251170290	NAMYSŁÓW	51.066	17.716	152	206.1	2.4 %
82	251190220	DOBRYSZYCE	51.148	19.408	216	255.5	2.9 %
83	251200270	DĄBRÓWKA STARA	51.780	20.737	174	218.1	2.5 %
84	251210120	PUŁAWY	51.413	21.966	142	23.6	0.3 %
85	251230120	BEZEK	51.177	23.264	224	938.5	10.7 %
86	252140160	TRZCIŃSKO-ZDRÓJ	52.964	14.588	55	481.0	5.5 %
87	252150050	KRZYŻ	52.881	15.984	30	99.3	1.1 %
88	252150180	LUBINICKO-ŚWIEBODZIN	52.243	15.545	88	118.1	1.3 %
89	252160110	SZAMOTUŁY-BABORÓWKO	52.584	16.638	75	387.4	4.4 %
90	252160230	WIELICHOWO	52.114	16.356	65	230.1	2.6 %
91	252190030	GŁODOWO	52.831	19.236	100	476.2	5.4 %
92	252200120	LEGIONOWO	52.408	20.956	94	159.0	1.8 %
93	252230030	BONDARY	52.938	23.754	147	216.7	2.5 %
94	252230120	BIAŁOWIEŻA	52.707	23.848	163	106.7	1.2 %
95	252230190	CICIBÓR	52.077	23.109	144	53.3	0.6 %
96	253140040	TRZEBIEŻ	53.663	14.514	1	394.3	4.5 %
97	253160090	WIERZCHOWO	53.460	16.104	137	184.0	2.1 %
98	253170210	CHRZĄSTOWO	53.161	17.584	105	869.0	9.9 %
99	253180020	RADOSTOWO	53.989	18.747	40	352.3	4.0 %
100	253180040	STAROGARD GDAŃSKI	53.982	18.549	100	333.7	3.8 %
101	253180090	ŚLIWICE	53.705	18.176	119	332.7	3.8 %
102	253180150	GRUDZIĄDZ	53.438	18.709	25	714.1	8.1 %
103	253180220	BYDGOSZCZ	53.174	18.046	55	111.0	1.3 %
104	253190030	DOBROCIN	53.908	19.828	118	223.9	2.6 %
105	253190220	LIDZBARK	53.254	19.824	140	81.1	0.9 %
106	253210210	MYSZYNIEC	53.384	21.350	120	158.5	1.8 %
107	253220070	BIEBRZA	53.651	22.578	115	409.9	4.7 %
108	253220270	JABŁONOWO-WYPYCHY	53.030	22.750	130	436.9	5.0 %
109	253220330	MARIANOWO II	53.212	22.106	138	223.4	2.5 %
110	253230020	RÓŻANYSTOK	53.635	23.401	160	271.3	3.1 %
111	253230160	SUPRAŚL	53.211	23.333	137	113.5	1.3 %

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Table 4 (*continued*)

#	Station ID	Name	WGS84_Latt [°]	WGS84_Long [°]	Altitude [m a.s.l.]	Mean annual generation [kWh/kW]	Capacity factor [%]
112	254160110	MIASTKO	54.016	16.980	160	114.4	1.3 %
113	254170040	KARŻNICZKA	54.488	17.229	75	1062.8	12.1 %
114	254170140	KOŚCIERZYNA	54.129	17.962	190	57.0	0.7 %
115	254180010	ROZEWIE	54.829	18.336	54	1739.3	19.8 %
116	254180060	GDYNIA	54.519	18.559	2	1027.2	11.7 %
117	254180140	OSTRZYCE-BRODNICA GÓRNA	54.274	18.091	213	536.6	6.1 %
118	254190050	FROMBORK	54.360	19.677	2	1179.2	13.5 %
119	254190120	KMIECIN	54.188	19.164	0	945.7	10.8 %
120	254190190	ELBLĄG	54.162	19.431	39	374.7	4.3 %
121	254200080	LIDZBARK WARMIŃSKI	54.136	20.586	90	214.6	2.4 %
122	254220030	GOŁDAP	54.308	22.269	159	371.2	4.2 %
123	254220090	OLECKO	54.048	22.487	182	500.7	5.7 %
124	349190600	BIELSKO-BIAŁA	49.807	19.002	396	648.6	7.4 %
125	349190625	ZAKOPANE	49.294	19.960	852	41.2	0.5 %
126	349200660	NOWY SĄCZ	49.627	20.689	292	86.3	1.0 %
127	349210670	KROSNO	49.707	21.769	330	351.3	4.0 %
128	349220690	LESKO	49.466	22.342	420	197.3	2.3 %
129	349220695	PRZEMYŚL	49.804	22.772	279	167.4	1.9 %
130	350150500	JELENIA GÓRA	50.900	15.789	342	344.8	3.9 %
131	350160520	KŁODZKO	50.437	16.614	356	640.0	7.3 %
132	350170530	OPOLE	50.627	17.969	163	213.9	2.4 %
133	350180540	RACIBÓRZ	50.061	18.191	206	617.2	7.0 %
134	350190550	CZĘSTOCHOWA	50.812	19.092	294	99.2	1.1 %
135	350190560	KATOWICE-MUCHOWIEC	50.241	19.033	278	233.8	2.7 %
136	350190566	KRAKÓW-BALICE	50.078	19.795	236	586.7	6.7 %
137	350200570	KIELCE-SUKÓW	50.811	20.692	260	190.5	2.2 %
138	350210585	SANDOMIERZ	50.697	21.716	217	275.0	3.1 %
139	350220580	RZESZÓW-JASIONKA	50.111	22.042	206	853.6	9.7 %
140	351150400	ZIELONA GÓRA	51.930	15.525	192	195.4	2.2 %
141	351160415	LEGNICA	51.193	16.208	123	531.3	6.1 %
142	351160418	LESZNO	51.836	16.535	91	512.0	5.8 %
143	351160424	WROCŁAW-STRACHOWICE	51.103	16.900	120	501.8	5.7 %
144	351180455	WIELUŃ	51.210	18.557	199	180.7	2.1 %
145	351190465	ŁÓDŹ-LUBLINEK	51.718	19.387	174	521.3	5.9 %
146	351190469	SULEJÓW	51.353	19.866	188	548.2	6.3 %
147	351220495	LUBLIN-RADAWIEC	51.217	22.393	238	331.1	3.8 %
148	351230497	WŁODAWA	51.553	23.529	177	699.9	8.0 %
149	352140310	SŁUBICE	52.349	14.620	53	289.8	3.3 %
150	352160330	POZNAŃ-ŁAWICA	52.417	16.835	88	768.2	8.8 %
151	352180345	KOŁO-RADOSZEWICE	52.362	18.706	110	545.8	6.2 %
152	352190360	PŁOCK	52.588	19.726	106	546.2	6.2 %
153	352200375	WARSZAWA-OKĘCIE	52.163	20.961	106	534.1	6.1 %
154	352220385	SIEDLCE	52.181	22.245	152	236.8	2.7 %
155	352230399	TERESPOL	52.079	23.622	133	182.2	2.1 %
156	353140200	ŚWINOUJŚCIE	53.923	14.242	6	771.3	8.8 %
157	353140205	SZCZECIN	53.395	14.623	1	466.3	5.3 %
158	353150210	RESKO-SMÓLSKO	53.764	15.393	52	498.4	5.7 %
159	353160230	PIŁA	53.131	16.747	72	94.2	1.1 %
160	353170235	CHOJNICE	53.715	17.533	164	526.0	6.0 %
161	353180250	TORUŃ	53.042	18.596	69	158.9	1.8 %
162	353200270	MŁAWA	53.104	20.361	147	445.0	5.1 %
163	353210280	MIKOŁAJKI	53.789	21.590	127	506.7	5.8 %
164	353210285	OSTROŁĘKA	53.066	21.534	94	153.0	1.7 %
165	353230295	BIAŁYSTOK	53.107	23.162	148	83.1	0.9 %
166	354150100	KOŁOBRZEG-DŹWIRZYNO	54.158	15.389	4	1504.2	17.2 %
167	354160105	KOSZALIN	54.204	16.155	33	442.7	5.1 %
168	354160115	USTKA	54.588	16.854	3	1712.9	19.5 %
169	354170120	ŁEBA	54.754	17.535	2	1676.8	19.1 %
170	354180155	GDAŃSK-ŚWIBNO	54.334	18.934	7	849.6	9.7 %
171	354190160	ELBLĄG-MILEJEWO	54.223	19.544	189	867.7	9.9 %
172	354210185	KĘTRZYN	54.067	21.367	107	648.5	7.4 %
173	354220195	SUWAŁKI	54.131	22.949	184	419.0	4.8 %

Load profiles are characterized as follows.

B	is intended for business customers who use medium-voltage power networks in their enterprises. The B21 tariff group, for example, is applied when the contracted power exceeds 40 kW.
C	is most commonly used by small and medium-sized businesses, as well as farms, whose energy needs do not require supply from medium- or high-voltage networks.
C11o	is for consumers are those with a constant power consumption, whose devices are controlled by dusk switches or control devices programmed according to: hours correlated with sunrise and sunset times or hours agreed upon with the consumer.
C12a	this tariff applies to consumers supplied from low-voltage power networks with a contracted power not exceeding 40 kW and a main circuit breaker rating of no more than 63 A. Billing for consumed electricity is based on a two-zone system, distinguishing between peak and off-peak hours.

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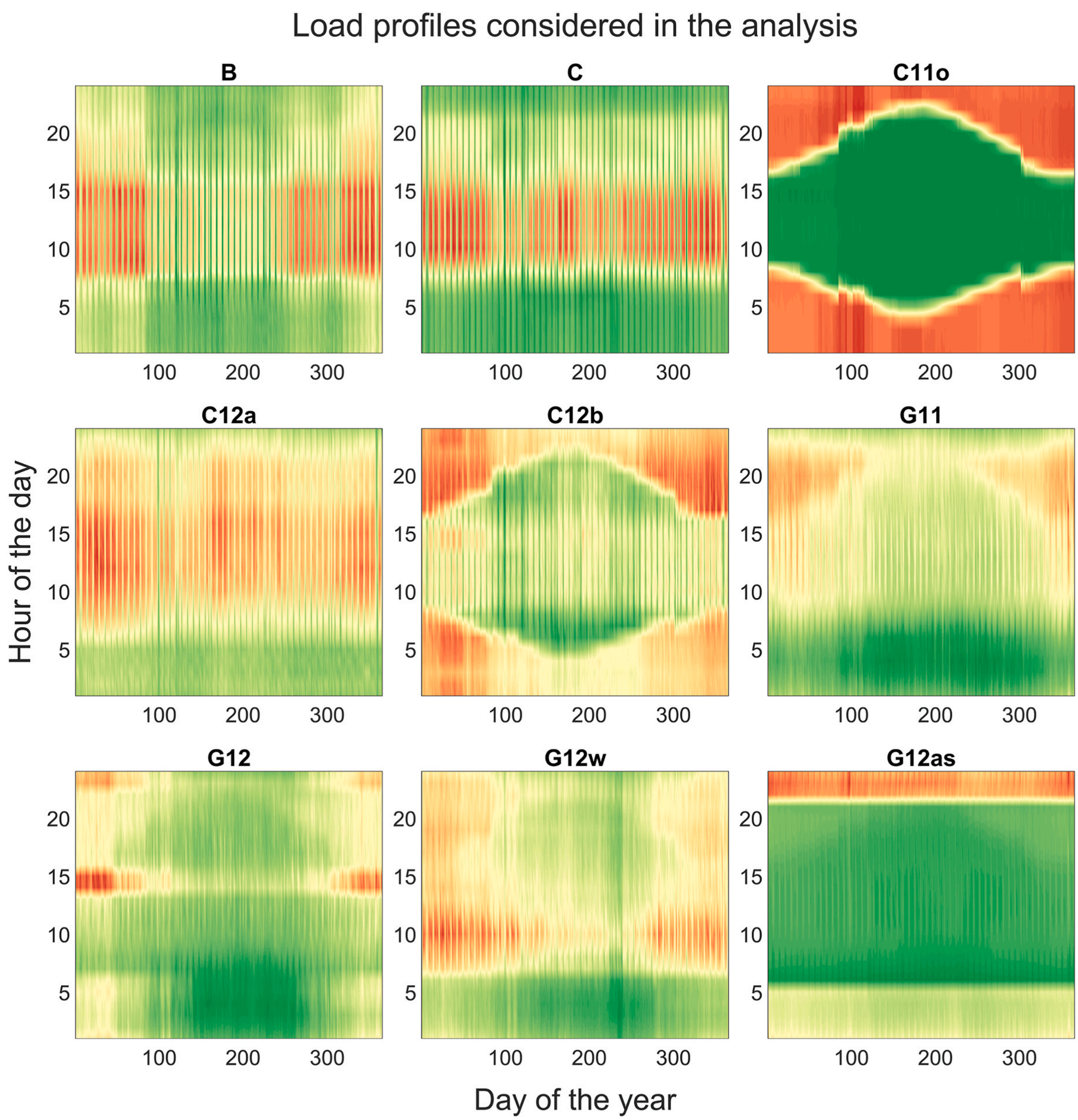
B	is intended for business customers who use medium-voltage power networks in their enterprises. The B21 tariff group, for example, is applied when the contracted power exceeds 40 kW.
C12b	Similar to C12a but the two-zone system, distinguishes between night and daytime.
G11	Regardless of the supply voltage and contracted power capacity, billing for consumed electricity under this tariff follows a single-zone system.
G12	Similar to G11 but with two zones (night and daytime)
G12w	As in G12 but electricity is also cheaper during the whole weekend and non-working days.
G12as	It is a special anti air-pollution tariff that guarantees lower electricity price from 10 p.m. to 6 a.m. for heating purposes.

What is important the Tariffs G apply to households, collective housing facilities (e.g., dormitories, monasteries, social care homes), residential-related utility spaces (e.g., basements, garages, staircases), seasonal homes and garden allotments, as well as lighting and elevator power in residential buildings, provided no business activity is conducted.

Fig. 1A
Various load profiles considered in the analysis of self-consumption and demand/supply matching. The color intensity goes from highest (red) to lowest (green) demand values.



Data availability

Data will be made available on request.

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