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Distributed generation as efficient measure to improve power generation adequacy

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Abstract: The article concerns safety of power supply for the final consumers, especially its two comprising elements, which are generation adequacy and distribution system reliability. Generation adequacy has been defined with Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE) and Energy Not Supplied (ENS) indices. Conclusions from generation adequacy forecast prepared by ENSTO-E for Poland compared with other European countries for the years 2020 and 2025 have been discussed along with the resulting threats. Interruptions in energy supply have been characterised by power discontinuity indicator SAIDI. Finally, a reliability and adequacy analysis have been performed for different scenarios of the Polish power system operation in order to assess possibilities of using distributed generation as a backup power source. Based on a simulation model created using the DIgSILENT Power Factory software, the reliability and adequacy calculations have been performed with the probabilistic non-sequential Monte Carlo method and they are followed by a discussion of the obtained results.

Key words: distributed generation, distribution system reliability, generation adequacy, local energy cluster, power supply safety

1. Introduction

When assessing power supply safety, all the elements of its delivery chain should be analysed, including various processes such as fuel extraction, energy generation, its transmission and distribution, ensuring competitive sale offers and their handling for the final consumers. The main task is to ensure sufficient generation adequacy in a given market area, taking into account the available capacity of cross-border interconnections. An important role in ensuring reliable electricity supplies from the power system to final consumers plays the efficiency of

Distribution System Operators' (DSO) performance, as one of the desired results are low values of electricity supply discontinuity indicators of the distribution network, which the customers are connected to. One of the most effective ways to prevent long-term failures due to necessary power line shutdowns is switching consumers to backup power supply. Due to the increasing share of distributed generation in covering loads in the power system and taking over responsibility for energy supply by local energy clusters, it is important to assess the possibility of using distributed resources as a back-up power supply and their impact on the security of electricity supply for local networks. This problem is analysed in the presented paper, considering mainly the availability of power generation to cover the existing demand and not considering the power dispatching tasks necessary to ensure the high power supply quality from the available sources.

2. Discontinuity of power supply problem formulation

The continuity of the distribution network's operation, which ensures the electricity supply to almost all customers, except for a few connected directly to the transmission network, is of key importance to limiting interruptions in final consumers energy deliveries. The distribution network is composed of radial power lines with an open tie point at their ends in most cases, and therefore damage in any of its branches causes interruptions in power supply to the customers until they are switched to a reserve feeder or, in the absence of a reserve, until occurring damages are fixed. In terms of reasons for power interruptions, it is possible to distinguish planned outages caused by the need to carry out necessary maintenance operations and unplanned outages that occur as a result of damage to network devices. When assessing the performance of distribution system operators, long breaks with a unit duration of more than 3 minutes are considered. Breaks longer than 24 hours are considered as catastrophic outages, usually associated with extensive failures caused by extremely difficult climatic conditions, the removal of which requires very intensive work of maintenance services for many hours.

The most commonly used indicator of power supply continuity in distribution networks is the system average interruption duration index, considering long and very long breaks of duration from 3 minutes to 24 hours, known as SAIDI. It is expressed in minutes per customer per year and for this period it is a ratio of a sum of encountered power recovery periods multiplied by the number of customers with a power supply break during a particular interruption and the total number of customers served by the DSO:

$$\mathrm{SAIDI} = \frac{\sum\limits_{i} (N_i T_i)}{N_T}, \tag{1}$$

where: T_i is the power recovery period for each distortion i [min], N_i is the number of customers with a power supply interruption during i^{th} distortion, N_T is the number of customers served by the DSO for which the index is determined.

The SAIDI index is also recorded in Poland, where distribution system operators are required to publish SAIDI values for their distribution areas for subsequent years since 2008. For the case of Poland the duration of planned outages for operational reasons is decreasing, but disastrous climatic conditions have a significant impact on the SAIDI values in particular years. In recent years, the value of the SAIDI index, including all outages' reasons reaches on average 300 to 400 min/c/a, but its maximum values get as high as 600–700 min/c/a for the regions most affected by disastrous climate conditions [12].

Attention should also be paid to the ways of limiting the power supply outage duration taking into account a relatively constant number of network failures that cannot be completely eliminated. Such a goal can be achieved by ensuring backup supply feeders or using distributed generation as reserve power sources and implementing effective automatic detection and isolation of damaged network sections associated with power supply restoration for network fragments without damage. Local distributed generation may also act as a backup power supply in case of distribution network outages, which is a subject of the following analysis.

3. Generation adequacy problem formulation

The integration of numerous distributed energy sources, energy storage, demand-side management cases and evolving legal regulations governing their operation, requires consideration of generation adequacy, as one of the indicators determining the security of power supply for final consumers. The generation adequacy is defined as the ability of the system to cover the demand for energy and power of consumers in a given time interval, for the steady state conditions of power system operation [1]. The generation adequacy has usually been determined only taking into consideration the capacity of conventional centrally dispatched power plants and the maximum load level of a given power system [1, 2, 3]. Nowadays, due to the growing number of renewable energy sources with a stochastic operation characteristics, it is necessary to include them in the generation adequacy assessment in a given area. The following probabilistic indicators [1, 3] are most often used to assess the generation adequacy:

– Loss of Load Probability (LOLP) – an indicator describing the probability that the demand will exceed the available generation capacity in the considered system states:

$$\mathrm{LOLP} = \sum_i p_i(P_{Gi} - P_{Li} \le 0), \tag{2}$$

where: p is the probability, P_G is the generation capacity [MW], P_L is the load [MW], i is the considered state of the system;

– Loss of Load Expectancy (LOLE) – an indicator defining the number of hours (if the LOLP indicator is determined for states of 1 hour duration) in a year, in which the energy demand cannot be covered due to lack of available generation capacities and import possibilities in a given area [h/year]; this index does not specify the severity of supply shortages:

$$\mathrm{LOLE} = \sum_i t_i p_i(P_{Gi} - P_{Li} \le 0), \tag{3}$$

where: t_i is the period when the load is bigger than available generation capacity [h]; $p_i(P_{Gi} - P_{Li} \le 0)$ is the probability of power generation deficiency in the system during the i^{th} hour of the year;

– Expected Demand Not Served (EDNS) – an indicator summing the values of uncovered power demand [MW], which occurred in the analysed system's operation states within their duration of 1 hour:

$$\mathrm{EDNS} = \sum_i \left(\sum P_{Li} - \sum P_{Gi} \right), \tag{4}$$

where: P_G is the generation capacity [MW], P_L is the load [MW], i represents states in the analysed system with power generation deficiency.

For the analysis assuming system state duration of 1 hour, equal to a market balancing period valid for the European cross border market, the EDNS index can be transformed into the Energy Not Supplied (ENS) index, which determines the amount of uncovered load [MWh] by generating units within the analysed hours; there is a problem of insufficient generation adequacy in the analysed system if ENS $\neq 0$.

Based on the data on generation and load levels in European countries, a generation adequacy forecast was prepared for the ENTSO-E area for 2020 and 2025, which is referred to as Mid-term Adequacy Forecast (MAF) [4, 5]. The forecast identifies and assesses threats to generation adequacy at the European level, as well as individually for each member state of ENSTO-E. The adequacy indices such as LOLE and ENS were determined based on the simulation of power systems' operating states using the probabilistic Monte Carlo method, which analyses various scenarios of generation capacity availability, load levels and cross-border exchange volumes for particular hours of the year. The generation adequacy analysis published in 2017 [5] was conducted for two cases: the base scenario and the mothballing scenario, which takes into account the risk of decommissioning many conventional power plants as a result of changes in the conditions and functioning of the energy market. Simulations performed for the baseline scenario, taking into account the forecasted rate of load increase, indicate that the greatest risk of generation capacities shortages in 2020 concerns island countries, such as Cyprus, Malta, Ireland and Northern Ireland, and the peripheries of continental Europe, i.e. Albania, Bulgaria, Greece and Finland. These threats are caused by the insufficient number and capacity of cross-border interconnections with continental Europe or too low number of conventional generating sources characterized by high operation stability. Detailed data on the values of LOLE and ENS indicators for Poland for 2020 and 2025 in accordance with the baseline scenario are presented in Table 1.

Table 1. Results of LOLE and ENS indicators for Poland in 2020 and 2025 obtained for the baseline scenario [5]

	2020			**2025**		
	Average	**Median**	**Value for the 95$^{\mathrm{th}}$ percentile**	**Average**	**Median**	**Value for the 95$^{\mathrm{th}}$ percentile**
ENS [GWh]	7.22	2.71	29.30	17.20	8.78	61.66
LOLE [h/a]	9.82	6.20	35.89	20.89	15.40	60.56

Due to unfavourable market conditions for conventional combustion plants, many of such units are threatened with decommissioning. The main reason is the shorter time of operation of conventional units facing covering of load consumption by the supported renewable energy resources, which affects the increasingly lower profitability of their operation. The factor imposing greater mothballing risk on the conventional units is also the lack of capacity market in some European countries. In the case of Poland, the most significant factor is introduction of stricter environmental standards regarding the emissions of nitrogen oxides, sulphur oxides and dust contained in the Best Available Techniques (BAT) conclusions. For large combustion plants these conclusions can be fulfilled only by investing in expensive flue gas treatment installations. For some generation units in Poland, costly adjustment to the emission requirements was unprofitable based on the market conditions in 2017. Even if the decisions were made to modernize large combustion plants in Poland, it would lead to a significant decrease in generation adequacy, due to the need for planned outages of these plants for the period of modernization [4]. The presented circumstances led to the creation of an alternative adequacy scenario for 2020 and 2025, referred to as the mothballing scenario [4]. According to the analysis [4], the risk of decommissioning concerns units constituting 15% of generation capacity in the ENTSO-E area. Although the mothballing risk applies only to 45% of the analysed countries, increased values of LOLE indicators after withdrawal of the considered units can be observed for 82% of the countries associated in ENSTO-E [4], which illustrates the importance of interconnection capacity concerning the generation adequacy for individual countries. In the Polish power system such unfavourable values of adequacy indices can be caused by numerous withdrawals of generating units, but also by the anticipated reduction of capacity of cross-border connections between Poland and Germany, Slovakia and the Czech Republic due to unplanned circular flows of electricity and lack of actions aimed at increasing the capacity of these connections. In the case of Poland, the delays in planned development of cross-border capacity in the south-west section may have a significant impact. With the import capacity reaching only 500 MW in this area in 2025, not 2000 MW as planned, the LOLE index increases by up to 270 h/year with the threat of increasing the ENS index by 280 GWh per year [4]. Finally, in the case of Poland, the LOLE indicator may reach the value of approximately 290 h/year, and the ENS indicator approximately 300 GWh in 2025 [4].

4. Influence of distributed generation on power supply safety

The problem of reliability and adequacy may directly affect electricity consumers, who can experience more and more severe interruptions in energy supply. One of the ways to avoid energy shortages caused by the unavailability of supply from the Polish power system is to install local renewable energy sources and to create local energy clusters responsible for their operation. Energy clusters are entities based on civil law agreement between consumers, energy generating entities, supply companies and local authorities, operating in the area not exceeding one county or 5 communes [6]. Dispersed renewable energy sources are installed in the operation area of these clusters, with the goal to supply the local customers with energy and thus enable partial or total independence from external electricity, heat or gas supply. Increased energy production at the local level aims at increasing competitiveness and economic efficiency of renewable energy sources and the local economy development but it can be beneficial to the local energy security as well. In addition, higher production costs in distributed generation sources will be partially offset by the reduced costs of external network transmission and distribution losses, taking place in the case of energy import from the power system. Verification of the possible effects mentioned above is necessary for each energy cluster individually to assess whether energy security and reliability of energy supply will be increased and to what extent the reliability and adequacy of the country power system has an impact on the performance of the energy cluster.

On the basis of the conditions concerning functioning of energy clusters presented in [6], an operation simulation of a fragment of the distribution network including renewable energy resources used by the local energy cluster was carried out. This network is additionally supplied from the external distribution network. The network model was created using the DIgSILENT Power Factory software. The scheme of the modelled network is presented in Fig. 1.

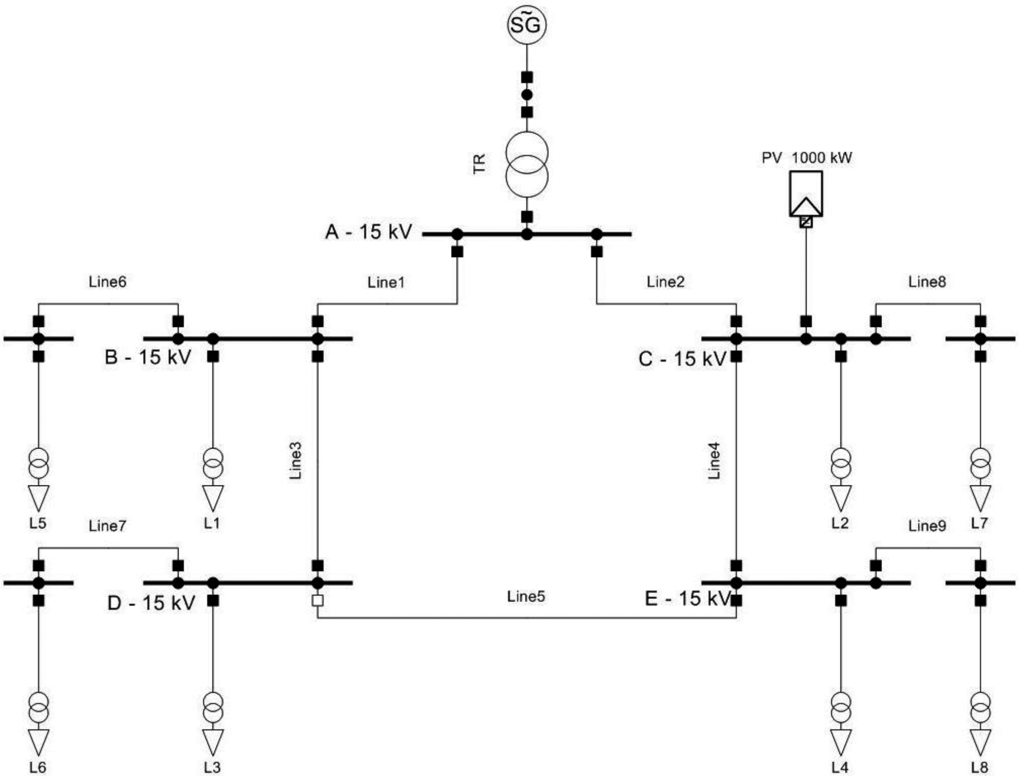

Fig. 1. The scheme of the modelled network

4.1. Load modelling

The modelled network supplies a group of 1000 household customers settled for electricity supply according to a flat tariff. The average annual consumption of each customer is 1806 kWh [6], and the daily load profile has been modelled on the basis of the standard load profile of customers from the flat tariff group of one of the Polish distribution system operators. The standard load profile determines the average relative energy consumption for every hour in the year in relation to the total annual consumption and presents the variability of the load of a representative group of households in the most adequate way. The analysis was also carried out for the same considered average annual customer's consumption, assuming that half of the load is generated by customers settled according to the two-zone time-of-use tariff, and the remaining part by the customers of the flat tariff. The total annual energy consumption in the second variant remains the same as for the first variant, because the aim of the research is only to analyse the influence of different load curve on the generation adequacy and reliability of the local power supply.

4.2. Generation modelling

The modelled local energy cluster operates a 1000 kW photovoltaic power plant, for which the generated power can be modelled based on the solar irradiance. The random behaviour of the solar irradiance can be modelled with a Beta probabilistic density function as presented in [7–9]. Based on the solar irradiance and the parameters of the plant, the power output of a photovoltaic module may be determined with following equations [9]:

$$P = g_s(s, \theta) = N \cdot FF \cdot V_y \cdot I_y \,, \tag{5}$$

$$I_y = s \cdot [I_{SC} + k_C(T_c - 25)] \,, \tag{6}$$

$$V_y = V_{OC} - k_V \cdot T_c \,, \tag{7}$$

$$T_c = T_a + s \cdot \frac{N_{ot} - 20}{0.8} \,, \tag{8}$$

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}} \,, \tag{9}$$

where: P is the power output [W], $g_s(s, \theta)$ is the solar generation function, s is the solar irradiance [kW/m^2], θ is the operation parameter vector of the photovoltaic module, k_V is the voltage temperature coefficient [V/°C], k_C is the current temperature coefficient [A/°C], FF is the fill factor [–], I_{SC} is the short circuit current [A], V_{OC} is the open-circuit voltage [V], I_{MPP} is the current at maximum power point [A], V_{MPP} is the voltage at maximum power point [V], N_{ot} is the nominal operating temperature [°C], T_c is the cell temperature [°C], T_a is the ambient temperature [°C], N is the total number of photovoltaic modules in the generator.

In the analysed example the annual energy generation profile was modelled on the basis of actual measurement data [10], which have been appropriately rescaled for the needs of 1000 kW installation. The annual power generation profile of the photovoltaic system under consideration, with nonzero values only for the daytime hours, is shown in Fig. 2.

Reliability of the photovoltaic system operation is determined as the probability of proper functioning of individual components, i.e. the probability of the full system's availability. The reliability index for photovoltaic farms, which is the probability of its proper functioning, is assumed at the average level equal to 71.4% [11]. At the same time, the PV-systems' unavailability, being the LOLP index for photovoltaic plant equals 28.6%.

The internal network of the considered energy cluster is connected to the external distribution network, which is a component of a country power system (CPS). Assuming various scenarios of

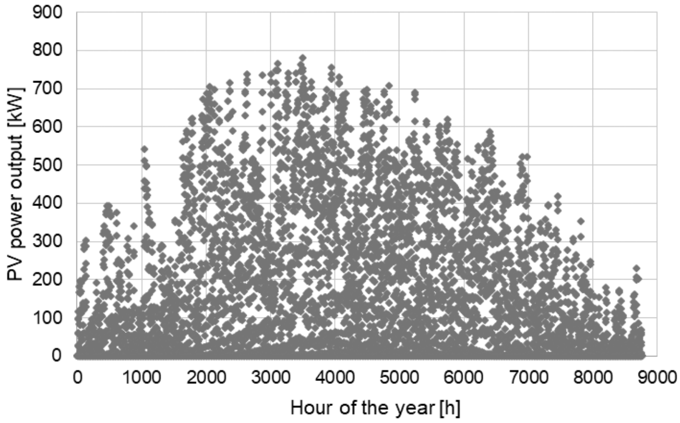

Fig. 2. Annual profile of power generation by a 1000 kW photovoltaic plant

the CPS's operation presented by ENSTO-E discussed earlier, analyses were carried out for the following variants of power supply reliability from the external network:

– variant 1 – reliability of the network operation is maintained at the 2017 level, reliability parameters are assumed for one of the Polish DSOs for the year 2017, SAIDI = 671.06 min/c/a [12],
– variant 2 – available generation capacities decrease in accordance with the baseline scenario of the operation of the ENTSO-E transmission networks, the case of Poland in 2025, LOLE = 20.89 h/a [5],
– variant 3 – available generation capacities decrease in accordance with the mothballing scenario of the operation of the ENTSO-E transmission networks, the case of Poland in 2025, LOLE = 290.89 h/a [5].

For the presented variants on the basis of reliability indicators of power distribution network and adequacy of generation indicators, the reliability models of the internal energy cluster distribution network were determined, in which the probability of occurrence of individual network operation states was determined in relation to the whole year. On this basis, the percentage time of reliable power supply and the occurrence of power interruptions were determined. The reliability parameters for individual variants are presented in Table 2.

Table 2. Reliability parameters of power supply from the external network in the considered network model

	Variant 1	**Variant 2**	**Variant 3**
Base indicator	SAIDI = 671.06 min/c/a	LOLE = 20.89 h/a	LOLE = 290.9 h/a
Period during which power supply from the country power system is unavailable – LOLP [%]	0.1277	0.2385	3.5490
Reliable power supply duration period [%]	99.8723	99.7615	96.4510

4.3. Analysis results

The summation of customers' daily standard load profiles and the electricity production profile from a solar farm allows determining the annual balance of energy supplies from the external distribution network, which is mainly dependent on the power output of the photovoltaic plant. The determined total load profile for consumers, consuming energy in accordance with the flat tariff's profile and the balance of energy supplied from the distribution network or from a solar source is presented in Fig. 3.

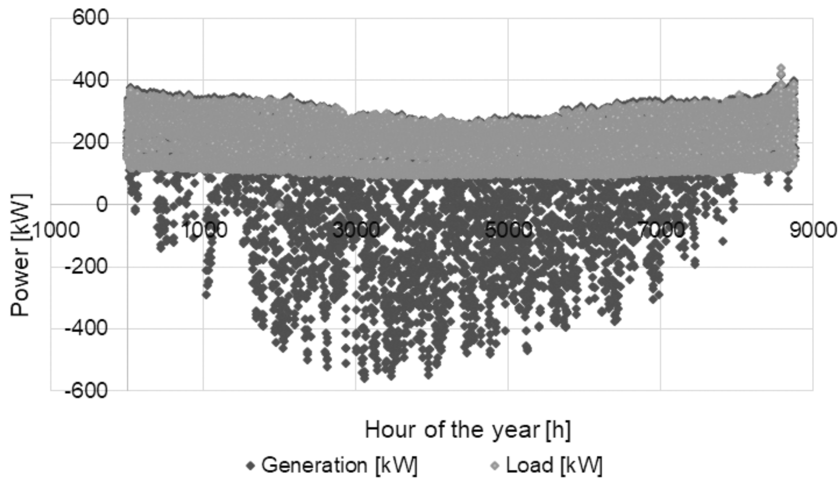

Fig. 3. Annual power balance in the network taking into account customers with flat tariff load profile and solar power generation

For the considered variants, generation adequacy simulations in the analysed network were carried out using the LOLP and EDNS indicators, assuming network system losses at the level of 3%. Adequacy simulations were carried out using the probabilistic Monte Carlo method, performing 100 000 simulations of random system states on the basis of which the above-mentioned indicators were determined. To ensure correctness of the results, 10 Monte Carlo simulations were performed for each variant, on the basis of which average values of LOLP and EDNS indicators were determined. The detailed formulation of the LOLP and EDNS indicators using the non-sequential Monte Carlo simulation is presented below [13]:

$$DNS = \sum P_L - \sum P_G, \tag{10}$$

$$\mathrm{LOLP} = \frac{N_{DNS}}{N} \cdot 100\%, \tag{11}$$

$$\mathrm{EDNS} = \frac{\sum DNS}{N}, \tag{12}$$

where: DNS is the uncovered load [MW], P_L is the load [MW], P_G is the generated power [MW], N_{DNS} is the number of iterations, for which $DNS > 0$, N is the total number of iterations.

Additionally, in Fig. 4, the probability distribution of particular load and generation levels for variant 1 with only flat tariff customers is presented, based on which it is possible to read the probability of a shortage in electricity supply being the point of intersection of the total load and the available generation curves.

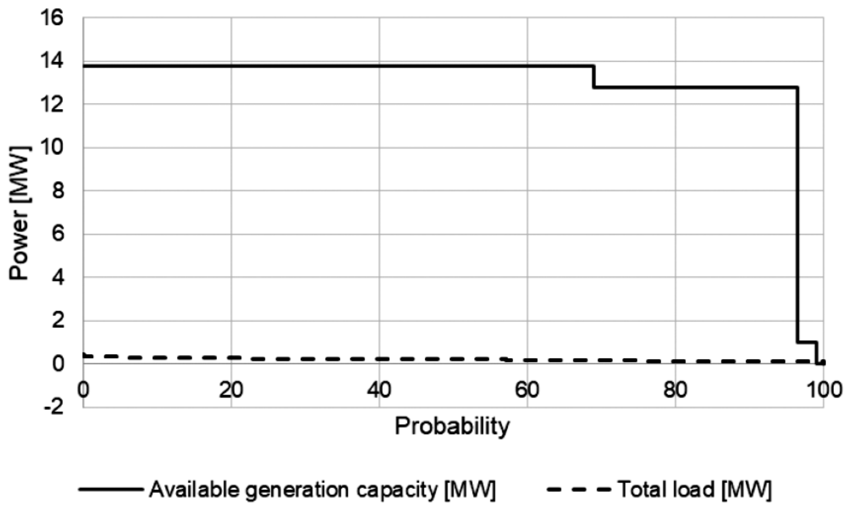

Fig. 4. Probability distribution of occurrence of certain system states based on Monte Carlo simulation

The generation adequacy simulation results are presented in Table 3. This table presents additionally the indicators of reliability of energy supply in the form of SAIDI indicators for the long duration breaks, the frequency of long duration breaks SAIFI and the amount of energy not delivered ENS, determined for the considered internal network. For this purpose, failure coefficients of internal network elements and average duration of repairs for overhead lines, MV

Table 3. Adequacy and reliability indicators for the considered network operation variants

Variant	**Variant 1**		**Variant 2**		**Variant 3**	
Year	**2017**		**2025 – baseline scenario**		**2025 – mothballing scenario**	
Customers	G11	G11/G12	G11	G11/G12	G11	G11/G12
Generation adequacy						
LOLP [%]	0.0347	0.0333	0.0687	0.0674	1.0184	1.0165
EDNS [kW]	0.071	0.0677	0.1424	0.1383	2.0916	2.0956
Reliability of electricity supply in the internal network						
SAIFI [1/c/a]	0.43641					
SAIDI [h/c/a]	0.129					
ENS [MWh/a]	0.029					

busbars and 15/0.4 kV transformers on the basis of [14] were introduced. For the considered network reliability variants, the indicators of adequacy and reliability were calculated for two types of customers' load: only consumers using electricity according to the load profile of the flat tariff and for half of customers using the flat tariff, and the other half the time-of-use tariff.

The obtained results of the generation adequacy indicators LOLP and EDNS, compared to the ones presented in Table 2, show the impact of distributed generation connected to the considered network on the generation adequacy of the considered energy cluster. The comparison of the analysis results for the generation adequacy indices is presented in the Fig. 5 for the considered cases. Ensuring adequate capacity of the energy cluster's connection to the external distribution network, which is most often limited by the rated power of the transformer and the capacity of power lines, allows one to use the energy available from this network freely and to adjust the consumption to the operation of distributed generation sources installed in the cluster network, as shown in Fig. 3. Only a significant reduction in the capacity of the connection to the external network, below the power demanded by the cluster's customers, results in a drastic decrease in adequacy in the analysed area [15]. The generation adequacy for the considered network presented in Fig. 5 is satisfactory, because the probability of energy shortage, in each case with the distributed energy resource integrated into the grid, is not higher than 1.02%. Such low values of adequacy indicators are caused by the connection of a distributed generation source in the analysed network, which provides back-up power at the peak of the power system load in case of discontinuity of power supply from the external network. Therefore, the installation of distributed sources has a very positive effect on the generation adequacy in the case of considered energy cluster, even for the case of a photovoltaic plant, which is characterized by a rather short daily energy generation time.

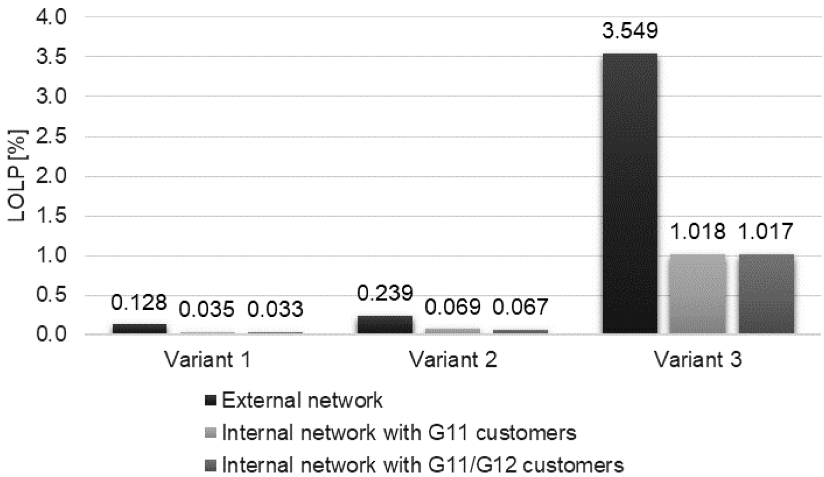

Fig. 5. LOLP values comparison for the internal analysed network and for the external network

For the considered level of reliability in 2017, characterised by SAIDI = 671.06 min/c/a, regardless of the energy consumption profile of the customers while maintaining the same total level of energy consumption, the system's adequacy remains very similar for the two considered customers groups of a flat tariff only and both flat and time-of-use tariffs. The resulting differences are caused by the stochastic method of determining LOLP and ENS indices and are within the limits of a statistical error. Along with the increase in the system's inadequacy in 2020 and 2025, the photovoltaic power plant has a very positive impact on the generation adequacy in the system, because it ensures covering the demand in the peak hours of the power system in summer, which falls between 10:00 and 18:00, i.e. at the peak hours of the photovoltaic plant performance. In winter, however, the influence of the photovoltaic plant on the generation adequacy is negligible, as the peak load of the power system occurs between 16:00 and 20:00 when solar energy is not available, so that it cannot improve the reliability of the system.

Limiting the availability of power supply from the distribution network, in accordance with the presented options, however, results in a decrease in the generation adequacy in the network, even in the case of support of generation from a local source. Limitations of the available generation capacities and the cross-border exchange capacity, as supposed for the ENSTO-E baseline scenario, can result in a double reduction in generation adequacy even in local distribution systems with integrated renewable energy sources. In the mothballing scenario, the probability of energy shortage and the amount of undelivered energy increases more than 30 times. If dispersed sources did not support the generation adequacy in the analysed network, energy shortages would be much more severe.

The reliability of power supply for the final consumer, determined with SAIDI and SAIFI indicators is also influenced by the reliability parameters of individual network elements. Due to the small area of the analysed network and the small number of network elements, the obtained indicators are characterised by very low values. However, the system under consideration is connected to the distribution network, which is characterized by much higher values of the above-mentioned indicators. The presented fragment of the distribution system cannot be considered individually, without taking into account the reliability of the entire distribution network. The SAIDI and SAIFI indicators remain unchanged for the considered simulation variants, regardless of the load profile of the connected consumers. It is due to the invariance of the parameters of the distribution network infrastructure, which determine the value of the reliability indicators.

Installing a solar power plant in the considered network is therefore crucial because of generation adequacy. Difficulties in covering the demand are most evident in summer from 10:00 to 18:00, i.e. at the daily peak load of the country power system, and in these hours dispersed generation, such as photovoltaic power plants which are the most efficient at this time may act as an important support for conventional generation capacities.

5. Conclusions

Increasing limitations for centrally dispatched generation of electricity based on conventional coal-fired power plants and important delays in the development of new transmission lines blocking the increase of power grid capacity cause the risk of a significant decrease of reliability of energy supply and generation adequacy in the country power system. Alarming ENSTO-E reports and disturbingly high power discontinuity rates of Polish distribution companies require the application of remedies taking into account the value of energy not delivered to customers. Network development, ensuring higher reliability of energy supply and access to the market offers of producers even from remote areas, has an alternative in the form of development of local energy sources.

The dissemination of distributed generation based on local renewable energy sources that can provide energy supplies to nearby consumers is a partial solution to reported problems of generation adequacy. However, it is necessary to take into account the stochastic nature of the dispersed renewable energy resources operation, dependent to a large extent on climatic conditions and the necessity to ensure proper operation of the local network with distributed sources connected to, which remains the responsibility of the energy cluster.

Safety of electricity supply can be supported by distributed energy sources, however, reliable functioning of a connection to the country power system must be ensured for the case of these sources, even to enable them exporting excess energy produced to the power system and not to limit the local consumers access to the competitive energy supply offers based on the proper functioning of the global energy market.

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