


Article

Analysis of Various Options for Balancing Power Systems' Peak Load

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Abstract: The balancing of the power of the Polish Power System (KSE) is a key element in ensuring the safety of electric energy supplies to end users. This article presents an analysis of the power demand in power systems (PS), with emphasis on the typical power variability both in subsequent hours of the day and on particular days and in particular months each year. The methodology for calculating the costs of electric energy undelivered to the end users and the amount of these costs for KSE is presented. Different possibilities have been analyzed for balancing power systems' peak load and assumptions have been formulated for calculating the amount of the related costs. On this basis, a comparative analysis has been made of the possibility to balance peak load using operators' system services, trans-border connections, and various energy storage solutions. On the basis of the obtained results, optimal tools have been proposed for market-based influence from transmission and distribution system operators on energy market participants' behaviors in order to ensure the power systems' operating safety and continuous energy deliveries to end users.

Keywords: power systems' load balancing; transmission system operators; system services; demand side response (DSR); peak power balancing costs



Citation: Majchrzak, H.; Koziol, M. Analysis of Various Options for Balancing Power Systems' Peak Load. *Energies* **2021**, *14*, 513. <https://doi.org/10.3390/en14020513>

Received: 7 December 2020
Accepted: 14 January 2021
Published: 19 January 2021

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1. Introduction

It can be concluded from the analysis of end user's demand for electric power and energy in a power systems that these values change both in subsequent times of the day and on particular days and in particular months each year. This variability results from the profile of end users' needs related to electric energy, and these, in turn, depend on many factors, including economic factors, i.e., conditions of their operation in a particular sector of the given country's economy, but also depend on the atmospheric conditions resulting from the season of the year, day of the week (working day, holiday) and the time of the day (night valley, intermediate load zones, and peak loads) [1].

In order to evaluate the scale of this phenomenon, the most important data regarding variability of the Polish Power System's demand in 2019 are presented in Figures 1–4, prepared on the basis of data published in annual reports on KSE operation by PSE S.A., the company serving as the Transmission System Operator (TSO) [2]. This phenomenon is applicable not only to the Polish system, which is confirmed by both experience and the profiles collected from the operation of the European power system, published by ENTSO-E (European Network of Transmission System Operators for Electricity) [3,4]. This is confirmed by experience of other transmission system operators (TSO, Transmission System Operators). Figure 1 presents daily demand curves in KSE on the days when the minimum and the maximum power demand occurred.

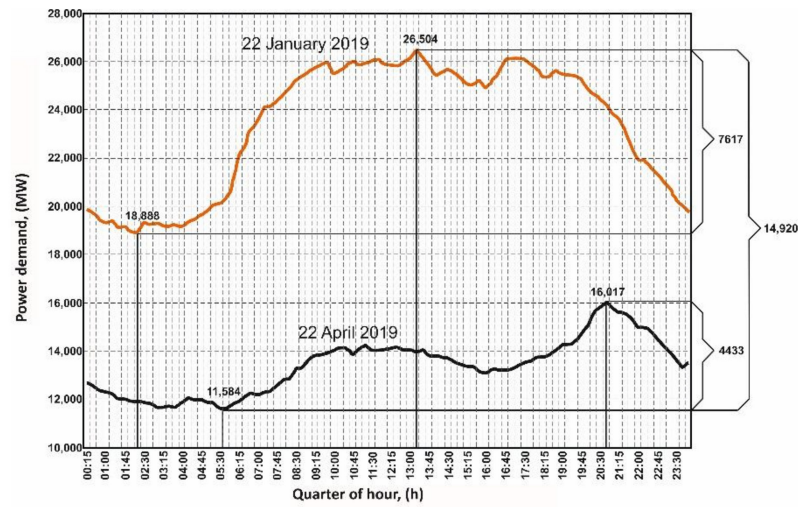


Figure 1. Power demand curves on the days when the minimum and the maximum domestic demand for power in the Polish Power System (KSE) occurred in 2019 [2].

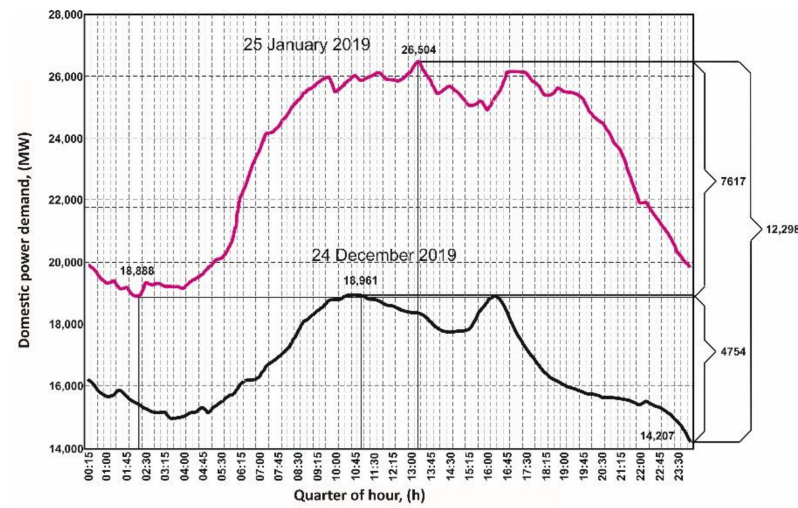


Figure 2. Domestic power demand curves for the day with the maximum and the minimum demand in the morning peak of a working day in 2019 [2].

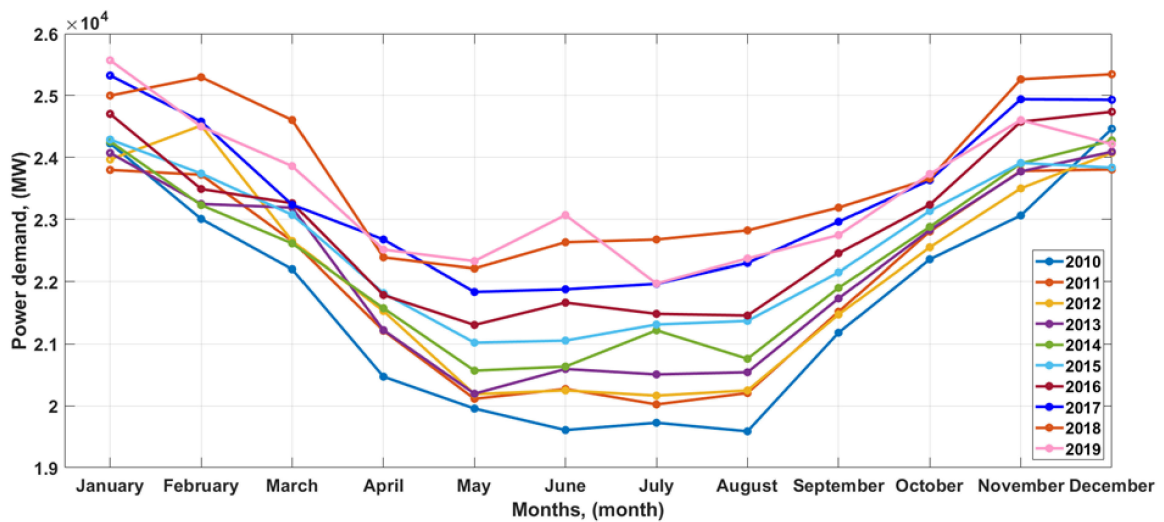


Figure 3. Average monthly power demand at daily peak loads in KSE on working days in the years 2010–2019 [2].

In the period concerned, the maximum power demand in KSE occurred on 25 January and reached 26,504 MW. Minimum domestic power demand occurred on 22 April and reached 11,584 MW. In the analyzed period, the difference between the maximum and the minimum demand amounted to 14,920 MW, i.e., approx. 56.3% of the peak demand. High variability of the power demand was also observed in at particular hours of the day. For the day when the maximum power demand was recorded, it was changing from 18,888 MW to 26,504 MW. For the day when the minimum power demand occurred in 2019, it was changing from 11,584 MW to 16,017 MW.

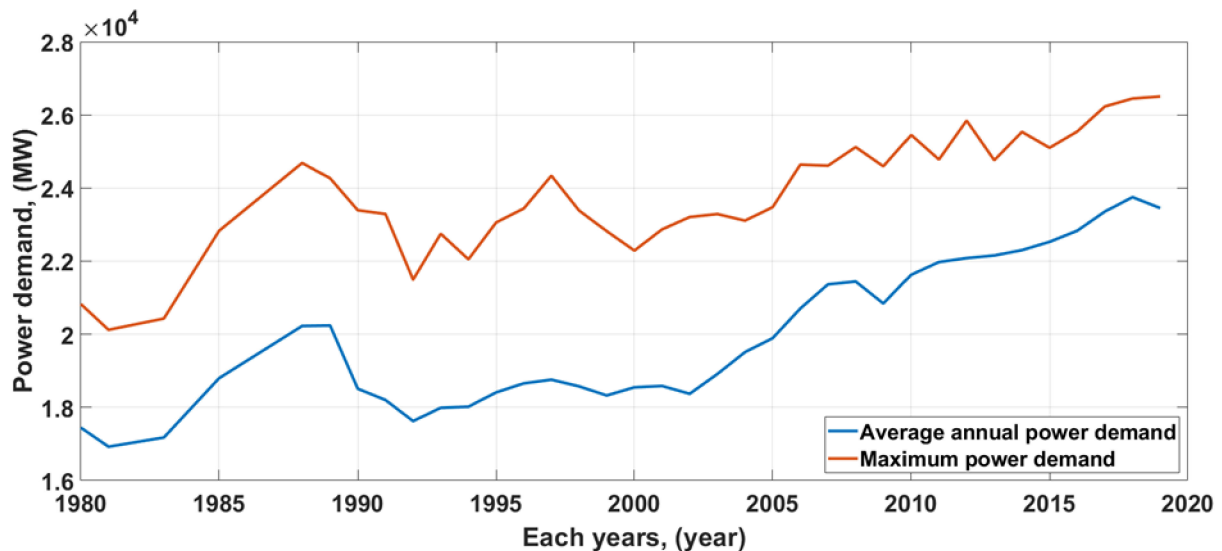


Figure 4. Average annual domestic power demand and the maximum values at daily peak loads on working days in the years 1980–2019 [2].

A comparative analysis of the data from 2019 against several previous years indicates a similar nature of the changes in the described power demand curves in KSE. In absolute terms, only a small growth in the share of gas power plants can be observed as compared to several previous years. Energy generation from wind power plants as well as other renewable sources is not subject to significant changes, being a result in particular of a small scale of building new generating units in this electric energy generation sub-sector. Figure 2 presents respective daily curves of the domestic power demand on the days when the maximum and the minimum demand was observed in the morning peak of a working day in 2019.

As it results from the presented peak demand charts, this value was changing from 26,504 MW, as on January 2019, to 18,961 MW, on 24 December 2019. Long-term data analysis indicates a characteristic, recurring in KSE, nature of the morning peak in the winter period, present around 10:00–13:00, the evening peak around 16:00–21:00, and the midday peak in the summer period at approximately 11:00–14:00.

Changes of the average monthly power demand at daily peak loads on working days in 2019 against historical data are presented in Figure 3.

Figure 4 presents an analysis of the average annual levels of the domestic power demand as well as the maximum daily peak load values on working days in the years 1980–2019.

The analysis of changes in the power demand at KSE peak loads in the period of the last dozen or so years clearly indicates a significant growth in the peak powers practically in all months of the year.

As it results from the presented data, the demand has been growing by 6 to 21% over the last 10 years. For many years the highest increases are recorded in the summer months, which is related to the growing market accessibility of air conditioning devices and cooling systems used in the industry, the services sector, and in households. The same conclusions

can be drawn from the analysis of the average annual levels of the domestic power demand as well as the maximum daily peak loads on working days in the years 1990–2019.

The problem area addressed in this article applies to a multi-variant analysis of the possibilities to balance power systems' peak load and formulation of the assumptions for calculations of the related costs. Optimal tools have been proposed for market-based influence from transmission and distribution system operators on energy market participants' behaviors in order to ensure safety of the power systems' operation and continuous energy deliveries to end users.

2. Methodology of Estimating the Costs of Electric Energy Undelivered to End Users

2.1. Limitations in Energy Supply to End Users

In the maintenance practice related to the problem area of balancing the PS power, many examples of limitations in electric energy supply to end users have been observed [5]. In the period 2015–2019, the amount of electric energy undelivered to KSE end users in the period of one year was changing approximately in the range 7–95 GWh, respectively accounting for 0.004–0.060% of the annual electric energy consumption in Poland [2]. Such situations are a consequence of many different events, including those caused, for example by more serious technical breakdowns in the generation, transmission or distribution sub-sectors, extreme weather conditions that cause significant limitations in the operation of key elements of the power system or generate extreme power demand increases, and improperly developed or too slowly implemented power system development plans [5]. In the event of potential difficulties in power balancing in PS, their operators, to maintain the expected deliveries to the end users, are obliged to take any possible actions [6]. Some of these actions are ad hoc operators' decisions, consisting in proper use of the means available at that time. Other ones are concerned with the development of mid- and long-term plans with the goal being to prepare for situations that may occur in a foreseeable future.

When preparing PS development plans, including for peak power balancing, it is necessary to estimate the costs of any possible limitations in the electric energy supply and consumption for the end users, as the awareness of the amount of these costs allows for determining the measures which should be taken in order to avoid these limitations.

The estimation of the effects of failure to deliver electric energy, including the costs of introducing limitations in electric energy supply and consumption for the end users, can be made using several methods, including on the basis of: historical events, statistical calculations, and questionnaire surveys.

2.2. Estimation of Costs on the Basis of Historical Events

The estimation of the costs of undelivered electric energy on the basis of calculations of the actual effects of any such situations in the past makes it possible to obtain results with a high level of confidence [7]. In order to utilize the so obtained results for further studies, they should be recalculated into the statistical conditions of a possible occurrence of the limitations in the future.

An example allowing for a relatively precise evaluation of the costs of undelivered energy in KSE is the extensive system breakdown in the Szczecin metropolitan area which occurred in 2008. The basic cause of the breakdown were extremely unfavorable weather conditions, caused by very large precipitation of wet snow and a very strong wind. Loads from the ice deposit on power wires and pole structures exceeded the catastrophic values of these loads adopted for the calculations by several dozen percent. As a result of the aforementioned atmospheric conditions, significant transmission and distribution system elements were destroyed in Szczecin and in a vast part of the West Pomeranian province, leaving approx. 512,000 end users without any electric power supply. The most severe shortages in the electric power supply affected households, for which the power supply restoration time was as long as seven days. The analysis of the economic effects of the event, prepared by a special team appointed under a decision of the Governor of the Western Pomeranian Province [8], covered as a broad spectrum of the entities and the related costs

as possible. The total financial effects of undelivered electric energy in the amount of approximately 4000 MWh were estimated at PLN 54.1 million, and the resulting unit cost of undelivered electric energy in emergency mode (*knea*) amounted to approximately 13,500 PLN/MWh. This analysis did not cover the effects of missing energy supply to households and agricultural farms due to the difficulty in estimating them, though these pauses undoubtedly generated losses. Statistical data concerning similar breakdowns in the USA indicate that in the estimation of the aforementioned unit costs it is possible to adopt the index equal to hundred times the price of electric energy delivered to an end user [3]. These calculations should be regarded as approximate (estimation accuracy evaluated by the source is around 20%), but very useful in the process of selecting the solutions improving the safety of electric energy supply to end users.

2.3. Estimation of Costs on the Basis of Statistical Calculations

The determination of the costs of undelivered electric energy may be based on calculations and estimates resulting from the economic conditions in which end users in particular branches of the industry and services as well as municipal end users operate. For this purpose, the information about business sectors can be used, available in published statistical data. The companies affected by limitations in electric energy supply sustain various losses, including, among others:

- reduced revenue in consequence of the limitations, suspended production,
- loss of contracts or penalties imposed for delays in processing orders,
- no possibility to use raw materials used in the suspended production process,
- no possibility to use the manufactured goods as a result of their destruction or value loss,
- other costs resulting from the need to make up for any lost production.

Under this methodology for the estimation of average unit costs of undelivered electric energy as a result of planned limitations, the amount of lost benefits for particular branches of the industry and services should be specified in the first place, as the quotient of their annual gross value added and the total annual electric energy consumption by these end users. The so defined amount is calculated in accordance with the dependence (1):

$$kne_p = \frac{GVA_p}{E_{ep}} \quad (1)$$

where

kne_p —unit cost of undelivered electric energy as a result of planned limitations, PLN/MWh,

GVA_p —annual gross value added of production in industry and services (gross value added), PLN,

E_{ep} —the amount of electric energy consumed in the industry and services in the period of one year, MWh.

Pursuant to legal regulations binding in Poland, limitations in electric energy supply and consumption on the territory of the Republic of Poland apply to electric energy end users with the contractual power above 300 kW. In this situation, for the Polish economy the estimated value of the index of the unit cost of undelivered electric energy as a result of planned limitations (kne_p) can be calculated as the ratio of gross added value of the production in industry (GVA_p) to the total amount of electric energy consumed in industry (E_{ep}), counted in the period of one year in Poland. At the same time, this is the average loss borne by the domestic economy under a forecast failure to deliver electric energy to industrial end users.

The so calculated amount should be regarded as an approximate index value, which can be lower in reality as a result of mutual compensations between particular interrelated industry branches, or trade exchange with foreign countries. To prevent the need to adopt expert assumptions reflecting these factors, the unit cost of undelivered electric energy for

the economy as a result of introducing planned supply limitations can be determined using the gross added value index for each industry sector. This results from the assumption that enterprises earn profit thanks to the manufactured products, expressed by gross value added. In computing the so calculated index not only the loss of profit resulting from the failure to manufacture and sell products should be considered, but also the losses related to losing the resources involved in the manufacturing, disturbed by the limitations in electric energy supply. The described method can be applied individually for each enterprise, thereby improving the accuracy in the calculated indexes for the whole economy. For industry sector i , this amount is specified by the aggregated gross value added attributable to a unit of energy consumed by this sector, according to the dependence (2):

$$kne_{pi} = \frac{GVA_{pi}}{E_{epi}} \quad (2)$$

where

kne_{pi} —unit cost of undelivered electric energy for industry sector i , as a result of the planned limitations, PLN/MWh,

GVA_{pi} —annual gross value added of industry sector i , PLN,

E_{epi} —amount of electric energy consumed in industry sector i within one year, MWh.

Each group of end users representing particular industry sectors, branches, sections is characterized by different levels of such indicators as

- production capacity utilization level,
- labor costs related to making up for the production which was not manufactured in connection with limitations in electric energy supply,
- costs of lost materials in connection with manufacturing downtimes and the increased energy purchase costs related to the increased production after the end of the electric power supply limitations.

The analysis of unit costs of undelivered electric energy calculated according to the above-described methodology should take consideration of the listed differences in the form of further appropriate corrections of the index calculated according to the following Formula (2).

As a result of the so conducted calculations, the approximate unit cost of undelivered electric energy as a result of planned limitations introduced by TSO in KSE in 2015 was estimated at approximately 7500 PLN/MWh.

Owing to the fact that the cost of undelivered energy also depends on the duration of the pauses and the frequency of their occurrence, these factors should also be considered in the final estimation of the average unit cost of undelivered energy.

It must be emphasized that, apart from the above-estimated pure financial effects, the introduction of limitations in electric energy supply and consumption also brings along other indirect consequences, including, among others:

- compromised image of the country in the eyes of prospective investors in terms of certainty of business operations,
- higher cost of financing investment projects, expressed by a higher capital cost adopted for performance analyses,
- higher cost of business operations resulting from necessary adaptation to possible limitations in energy supply.

These losses depend on many factors and are difficult to be estimated directly, but undoubtedly have a long-term effect on the condition and competitiveness of the economy as well as the given country's investment attractiveness.

Another possibility to estimate the effects of failure to deliver electric energy is conduct of detailed questionnaire surveys, with which the end users covered by the potential limitations would estimate these effects, based on their own calculations and experience. On the basis of the so collected representative survey data, incorporating a sufficient

number of end users in any group, it is possible to make good estimates of the unit cost of undelivered electric energy.

Power systems' development plans, including for power balancing, should include estimates of the costs of limitations in the electric energy supply and consumption for the end users.

The results of the estimates presented in items 2 and 3 indicate that the financial effects of electric energy supply and consumption limitations for end users in Poland are at the level of approximately 7500–13,500 PLN/MWh.

The analysis of direct and indirect financial effects of limitations in electric energy supply and consumption for the end users clearly indicates that possible preventive actions performed early enough are much less severe, both socially and economically [8,9].

3. Utilization of System Services for Peak Power Balancing

3.1. The Role of System Operators in Ensuring Continuous Energy Deliveries

TSO is an energy company engaged in the transmission of electricity, also responsible for network traffic in the power transmission system, as well as for the current and long-term security of the system's operation. One of the key tasks of the TSO is balancing the power system, determining and ensuring availability of appropriate reserves of generation, transmission and interconnection capacities for the purpose of balancing the current demand for electricity with the supply of that energy and conducting settlements resulting from imbalance of electricity supplied and received from the national power system.

As part of this task, the TSO maintains the so-called automatic frequency and active power control system in connected power systems. The task of this system is to maintain the frequency and, above all, to keep the established balance of the intersystem exchange, in accordance with the adopted algorithm. The regulation of frequency and power in the power system is carried out by means of coordinated influence on the level of generation of active power of generating units. Primary and secondary regulation is realized under the conditions of normal system operation through the coordinated influence of the central controller on the individual regulators of selected generating units. All technical details for generation units providing regulatory system services are specified in a publicly available TSO document: Transmission System Operation and Maintenance Manual.

In order to ensure an adequate volume of system services, the TSO signs transmission contracts with the generators that guarantee its access to the required generation unit regulation. The operators of these units are required to keep their regulatory systems ready to provide such service. At the same time, the TSO periodically organizes public tenders for the purchase of specific services, which allow it to use its regulatory capacity, according to the rules approved by the Energy Regulatory Office in the operator's transmission tariff.

The required amount of operational power reserve and the required scope of primary and secondary regulation are determined by the TSOs on day $n-1$, based on the ENTSO-E (The European Network of Transmission System Operators for Electricity) guidelines and system analyzes.

Under these rules, the following general requirements apply to the KSE:

- operational power reserve: 9% of planned demand to be covered by domestic power plants,
- primary control range-about 170 MW,
- secondary control range-about 500 MW.

In the event of potential difficulties in balancing PS power, their operators, to maintain the expected deliveries to the end users, are obliged to take any possible preventive actions, such as, for example, emergency imports from other PS's, use of the option to overload working generating units and launching emergency units, voltage reduction in the power supply grid for a certain group of the end users, stopping works conducted in these parts of the PS which result in the available power limitations. However, if all possible preventive actions prove insufficient, the system operator is obliged, in order to ensure safety and stability of PS operation, to apply further measures, including limitations in electric energy

supply and consumption. These limitations are introduced in a manner consistent with the plans prepared for this purpose, subsequently starting from scheduled limitations and then, when necessary, applying emergency limitations.

Operators also try to ensure the level of safety $n-1$, whose main objective is to secure the power system and ensure continuity of electricity supply to end users in the event of failure of one energy source. It assumes that the failure of e.g., the largest generating unit may not disrupt the operation of the entire power system.

3.2. Basic Peak Power Balancing Mechanisms in the Polish Domestic Power System

In each power system, there may be temporary problems with guaranteeing a safe power balance margin, which in extreme cases will lead to the introduction of the mechanisms for limitations in electric energy supply and consumption. The probability of these undesired situations is much higher in the periods of peak PS loads, a typical feature of which is short duration. The statistical data collected for the period of the last few years of KSE operation indicate that the peak demand, lower by no more than 500 MW from its maximum value in a year, was present for about 20 h per year only, and, respectively, by 1000 MW-for about 100 h per year. These data indicate the assumptions to be taken into consideration for the economic studies examining different options to cover the power demand in the system.

Decisions to build peak sources are made very often in order to balance the peak demand. Considering a very short duration of their utilization, the costs of generating emergency-supplied electric energy are very high. The construction of peak sources by PS operators, in spite of a significant amount of these costs, results most often from a great fear of the economic, social, and especially image-related effects of the failure to ensure continuous energy deliveries to end users. To avoid wrong decisions being made under the pressure of the aforementioned circumstances, it is very helpful to develop a model allowing to determine the unit costs of the peak power balancing system services in the system, for various solution options [10,11]. This model should be designed so as to ensure that it is possible on its basis to compare the possible solutions well and indicate the best one among them.

Based on the solutions applied in recent years in KSE, it is possible to distinguish the most important PS peak power balancing methods:

1. work with centrally controlled generating units (UPP) being overloaded,
2. the service of availability of the generating units not being centrally controlled by TSO (GWS),
3. operator's import of electric energy on the basis of separately concluded inter-operator agreements on synchronous connections (OIPs),
4. the system emergency service "cold reserve"-the effect of two public tenders conducted by TSO (IRZ2),
5. reduction in demand to the order of TSO (DSR, demand side response),
6. emergency operation of a new generation source dedicated for peak operation: (ZISno), oil-fired,
7. emergency operation of a new generation source dedicated for peak operation: (ZISng), gas-fired,
8. use of new trans-border connections within the binding principles of operation of the European electric energy market (PTn),
9. use of pumped storage power plants used in KSE, on the basis of separate agreements concluded by TSO (PSH).

In order to present this problem area, commonly available data have been collected here, concerning the solutions applied in KSE, and comparative studies have been made on their basis. The choice of the possible solutions has been made so that they could be used as a model suitable for similar analyses for other power systems. For this purpose, necessary calculations have been made, respectively for: system services available in KSE for the needs of TSO (items 1, 2, 4, and 5), the operators' import of electric energy which is

not a system service as defined in IRiESP (Transmission Grid Operation and Maintenance Instructions) but serves its basic functions (item 3) and the potential emergency operation system service provided by generation sources dedicated for peak operation (items 6, 7). The selected results of the aforementioned calculations, made for 200 h of services utilized in a year, have been collected in Table 1 and presented in Figure 5. The designated power balancing costs include all costs of providing services, i.e., fixed and variable costs. Fixed costs include those costs the amount of which is independent of the working time of a given source, e.g., depreciation, capital costs, maintenance, and operating costs. Variable costs are those costs which are depending of the working time of the source, e.g., costs of: fuel used, charges for environmental emissions, electricity used for own consumption. Gross costs are respectively the sum of the above mentioned fixed and variable costs.

Table 1. Statement of the unit costs of power balancing by KSE system services in 2015 [12].

Type of Service	Unit Cost of Power Balancing by System Services (For 200 h in a Year)			
	Fixed	Variable	Gross	Net
	(PLN/MWh)			
Overload operation service (UPP) Generation forced by system considerations (GWS)	–	200	200	40
Operators' import of electric energy on synchronous connections (OI_{ps})	–	520	520	360
Emergency "cold reserve" (IRZ2)	880	300	1180	590
Demand reduction to the order of TSO (DSR)	–	1160	1160	1160
New peak emergency source-oil fuel powered (ZISno)	2060	650	2710	2550
New peak emergency source-liquid gas fuel powered (ZISng)	2060	940	3000	2840
Unit cost of undelivered electric energy: scheduled limitations (k_{nep})-unplanned (emergency) limitations (k_{nea})			7500–13,500	

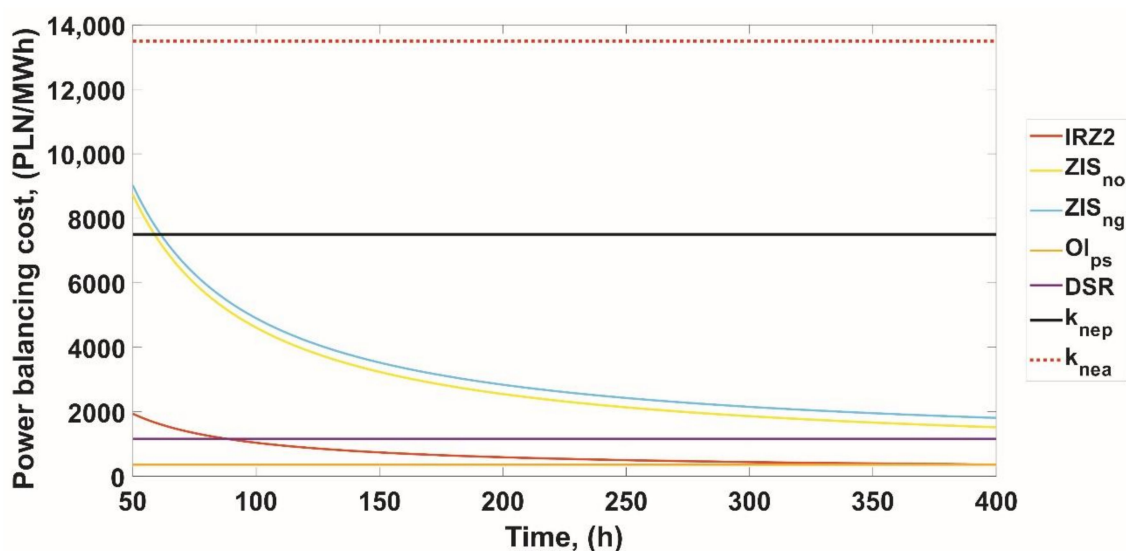


Figure 5. Dependence of the net unit fixed cost of power balancing by system services on the services utilization time in KSE (prepared by the author).

On the Figure 5, in order to preserve its transparency, the presentation of the first two services (UPP and GWS) has been hidden, as for them the lowest unit cost in the group of the solutions being compared strongly depends on the market regulator's decisions. Although their amount depends on the decision of the market regulator, they are subject to tariffs, but they are not ignored by TSO. As the cheapest solution, they are even used in the first place, as long as they are available on the day when the operator uses system services to balance the power. In the author's previous works [5,12,13], the main mathematical assumptions concerning unit balancing costs were derived and proven in detail, and possible general assumptions for further analyzes of this type were proposed, which were concerned with the year 2015. The obtained results give a good basis for the analysis and comparisons also in 2020, as the differences in the input data recorded at that time apply only to electric energy prices on the balancing market (average price on BM for the year 2019 increased as compared to the year 2015 by approximately 75 PLN/MWh and respectively amounted to 235 PLN/MWh), and its effect on the results of the calculations does not change the conclusions regarding the comparison of different solutions. All the presented services are much cheaper than the unit cost of undelivered energy, therefore, their contracting should be within TSO's permanent interest.

In order to balance peak loads, generation units intended for peak operation are commonly used, characterized, in particular, by low unit investment outlays, high availability, and short start-up time.

Considering the short duration of the peak demand, it is necessary to search for cheaper alternative solutions. For this purpose, unit power balancing costs can be used, in order to compare various solutions on this basis.

The analysis of the unit costs of power balancing by system services shows that a more favorable alternative to the construction of generating units dedicated for peak operation is in particular: overload of the generating units intended for basic operation operating on the market, utilization by the operator of the possibility to render the power balancing system services by distributed generation units, emergency energy imports from other PSs on the basis of separate inter-operator agreements, temporary use for emergency operation of generating units planned for liquidation, the application of demand side response mechanisms.

4. Utilization of Trans-Border Connections to Cover Peak Power

4.1. Strategy Regarding Creation of the Energy Union

Announced in 2015, the Energy Union concept proposes many further legislative changes required to implement the key ideas it promotes: energy security, integrated energy market, energy efficiency, decarbonization of the economy, and promotion of research and innovation [14].

For this purpose, the European Commission has adopted a framework strategy for stable energy union combined with the policy of counteracting climate changes and has issued a communiqué within it, concerning the goal in the form of inter-system power connections with the capacity of 10% of the installed power of all generating units in the power system [15]. When setting this goal, it was acknowledged that the European power grid with inter-system connections is of fundamental importance for the energy security of Europe, increased competition, the aim of which is to keep as low prices as possible and efficiently pursue the goals of the policy of decarbonization and counteracting climate changes. The European Commission's communiqué includes the implementation strategy for the goal it sets.

A higher degree of market integration caused by the functioning of trans-border connections also reduces the need for investing in new generating capacities and other systems, e.g., for energy storage, necessary to cover PS peak loads. Trans-border connections can also be utilized to provide the balancing services of the neighboring systems, allowing for reduction in their short-term operating costs. It is estimated that lower electric energy

prices for enterprises and households obtained as a result may, in the time horizon until 2030, bring annual savings to customers in the amount of EUR 12–40 billion [16].

The European Council has assumed that the target level connections should be achieved mainly by the implementation of projects being in common interest (PCI) and utilization of the Connecting Europe (CE) financing instrument. In this way, an efficient mechanism has been created for defining and implementing European priority transmission corridors. The first list of these projects adopted in 2013 included 248 positions, 52 of which are inter-system power connections. It was assumed that most of the mentioned projects are to be completed until the end of 2020.

The European Commission takes further efforts, which assume the end of creation of the internal electric energy market, in particular elimination of energy islands existing in Europe and an increased share of electric energy generation from renewable energy sources. The EU's efforts must be focused on achieving inter-system connections at the minimum level of 15% by all the Member States until 2030.

4.2. Costs of Power Balancing Using Trans-Border Connections

In order to make an analysis of the various options for covering KSE peak power demand, in the context of utilizing trans-border connections for this purpose, apart from the investment outlays for the construction of lines and the line-related transmission grid infrastructure, it is necessary to consider all other costs related to their construction and maintenance. This analysis should include, in particular: operating costs, depreciation, return on invested capital, costs of electric energy losses related to energy transmission and other costs.

In order to calculate the unit costs of power balancing by trans-border connections the following dependencies can be used (3), (4):

$$k_{bm_{pt}} = k_{bm_{pts}} + k_{bm_{ptz}} \quad (3)$$

$$k_{bm_{pts}} = k_i \frac{(A + \frac{r}{2} + k_{M\&O})}{100 t_{zm}}, \quad (4)$$

where

$k_{bm_{pt}}$ —unit cost of power balancing by trans-border connections, PLN/MWh,

$k_{bm_{pts}}$ —unit fixed cost of power balancing by trans-border connections, PLN/MWh,

$k_{bm_{ptz}}$ —unit variable cost of power balancing by trans-border connections, PLN/MWh,

k_i —unit investment expenses proportional to the line transmission capacity, PLN/MW,

r —weighted average cost of capital adopted in the operator's tariff, %,

$k_{M\&O}$ —unit costs of operation and maintenance expressed as percent of unit investment expenses, %,

A —depreciation rate determined for the assumed operation period, %, and

t_{zm} —time of using the connection to cover peak loads in a year, expressed in hours, h.

In the case of trans-border connections it is correct to adopt the simplifying assumption, which equals the gross and net amounts of the power balancing unit cost. The term the net unit balancing cost is defined as the gross cost less TSO's revenue under sale of electric energy. The distinction of these terms is important in the situation when, along with the power availability service, the operator's also buys electric energy, which it later resells on the market. Commercial terms of international transactions do not generate additional variable costs sustained by the system operator. The results of calculations of the unit power balancing costs are specified in Table 2, where the unit power cost indicator is also included for particular connections, trans-border (km_{pt}) calculated according to the following Formula (5):

$$k_{m_{pt}} = k_i \frac{(A + \frac{r}{2} + k_{M\&O})}{100}. \quad (5)$$

Table 2. Comparison of unit costs of the various options for expansion of KSE trans-border connections (prepared by the author-data for 2015).

Trans-Border Connection	Unit Investment Expenses (k_i)	Unit Costs of Operation and Maintenance ($k_{M\&O}$)	Unit Cost of Power Balancing (For 200 h in a Year) ($k_{bm_{pt}}$)		Unit Power Cost
	(PLN/MW)	(%)	Gross (PLN/MWh)	Net (PLN/MWh)	(Thousands PLN/MW Annual)
Poland-Lithuania (500 MW)	932,000	1.9	3790	3790	758
Poland-Lithuania (1000 MW)	466,000	(1.8–2.0)	1895	1895	379
Expansion of KSE's western part	440,000		1820	1820	364
Construction of 3rd connection Poland-Germany	455,000		1770	1770	354

The factor $1/2$ given in Equations (4) and (5) results from the applicable rule of determining with the President of the Energy Regulatory Office (ERO) the so-called Regulatory Asset Value (RAV), which is the basis for calculating the return on capital in the TSO tariff. This value is determined on the basis of the net asset value of the transmission operator's assets as of the last day of the year preceding the year for which the tariff is approved (the net value is the gross value reduced by depreciation accrued in previous years). Depreciation is calculated using the straight-line method, so the average return on capital for such an account requires the application of the above factor. In the case of a market-based formula for determining such a cost, i.e., not regulated by the energy regulator, the cost of the assets involved is calculated from their full value, i.e., without the $1/2$ factor (e.g., Formula (7)).

A significant element in the further development of the European electric energy market is expansion of the trans-border infrastructure of European power systems. Trans-border connections may play an important role in the process of covering KSE peak power demand. In order to compare them with other possible solutions, it is necessary to analyze all costs related to the construction of trans-border lines and their accompanying transmission grid infrastructure as well as their future maintenance and operation costs

5. Utilization of Energy Stores for KSE Peak Power Balancing

5.1. The Role of Energy Storage in the Development of Power Systems

Regardless of the multiple conditions that affect the pace of development of renewable energy sources, many circumstances, including the assumed international commitments related to the pursued climate policy, show that in the future the share of renewable energy sources in the power balance will be systematically growing. Within the group of effective mechanisms mitigating the effects of unstable RES operation, employing new, promising technologies, special attention should be paid to energy storage systems. These technologies are characterized by high reliability and operating flexibility as well as the possibility of simultaneous fulfillment of many other functions which the operators managing the operation of the power system are responsible for. The most important ones include: adjustment of the system's voltage and operation frequencies, elimination of grid limitations, preventing limitations in energy supply to end users, restoration of the normal operation after system breakdowns.

The circumstances provided above create a real perspective for energy storage technologies to be more broadly utilized for the needs of optimization, development and operation of PS. In this area, energy stores should also be taken into account by TSO as one

of possible technical solutions, used for PS emergency peak power balancing, i.e., in the conditions when the normally functioning electric energy market does not ensure coverage of the loads required by the end users.

5.2. Costs of Power Balancing Using Energy Stores

The economic assessment of the energy storage solutions for peak power balancing, currently used in KSE and those that can be acquired on the market, can be made based on the analysis of unit power balancing costs of energy stores drawn up on the basis of the data regarding KSE. In order to determine the aforementioned index, the following dependencies have been used Equations (6)–(11):

$$kbm_{meb} = kbm_{mes} + kbm_{mez} \quad (6)$$

$$kbm_{mes} = k_i \cdot \frac{(A + r + k_{M\&O})}{100 t_{zm}}, \quad (7)$$

$$kbm_{mez} = be_{me} c_e, \quad (8)$$

$$be_{me} = \frac{1}{\eta_{me}}, \quad (9)$$

$$kbm_{AESz} = k_{sp} c_e + k_g c_g, \quad (10)$$

$$kbm_{men} = kbm_{meb} - c_{RB} - c_{ORM}, \quad (11)$$

where

- kbm_{meb}, kbm_{men} —unit gross, net power balancing cost by energy storages, PLN/MWh,
- kbm_{mes}, kbm_{mez} —unit fixed, variable power balancing cost by energy storages, PLN/MWh,
- k_i —unit investment expenses relative to the store's installed power, PLN/MW,
- r —weighted average cost of capital, %,
- $k_{M\&O}$ —unit costs of operation and maintenance expressed as percent of unit investment expenses, %,
- A —depreciation rate relative to the assumed operation period, %,
- t_{zm} —store's usage time expressed in hours in a year, h,
- be_{me} —unit electric energy consumption index to fill the store,
- η_{me} —efficiency of an energy store with electric energy supply only (battery),
- kbm_{AESz} —unit variable power balancing cost by energy storages for CAES, LAES plants, utilizing electric energy and gas, PLN/MWh,
- k_{sp} —electric energy consumption index for driving the compressor per electric energy unit taken out from the store,
- k_g —fuel gas chemical energy consumption index per electric energy unit taken out from the store,
- c_e —average purchase price of electric energy on the market for the needs of charging the store, PLN/MWh,
- c_g —average purchase price of the gas consumed in CAES, LAES systems, PLN/MWh,
- c_{RB} —average selling price of electric energy on the balancing market (RB), PLN/MWh, and
- c_{ORM} —average price of operating power reserve service calculated for the assumed service utilization time (t_{zm}), PLN/MWh.

Table 3 presents the results of calculations regarding unit fixed and variable power balancing costs (kbm_{mes}, kbm_{mez}) specifying the gross amounts, which take account of all the incurred costs (kbm_{meb}) and the net amounts (kbm_{men}), i.e., with costs reduced by revenues from sale of electric energy by TSO to the balancing market as part of the provided service and by the avoided costs of purchasing the operating power reserve. The presented results, just like in Tables 1 and 2, apply to the service utilization time in a year amounting to 200 h. Detailed assumptions adopted for the calculations have been presented in the monograph [12]. It should be emphasized that some assumptions had to be updated for the year 2020, which has resulted in the need to make repeated calculations for averaged

oil fuel and electric energy and gas prices valid in 2019 being the subject matter of the transactions on TGE (Energy Commodity Exchange) and RB. The obtained results have been presented in Table 3.

Table 3. Statement of the unit costs of power balancing by energy storages in 2020 (prepared by the author).

Type of Energy Store	Unit Power Balancing Cost (For 200 h in a Year)			
	Fixed ($k_{bm_{mes}}$)(PLN/MWh)	Variable ($k_{bm_{mez}}$)(PLN/MWh)	Gross ($k_{bm_{meb}}$)(PLN/MWh)	Net ($k_{bm_{men}}$)(PLN/MWh)
Pumped storage power plant (PSH)	6550	256	6806	5941
Advanced acid-lead battery (La)	8775	256	9031	8796
Sodium-sulfur battery (NaS)	7875	256	8131	7896
Lithium-ion battery (Li-Ion)	5030	228	5258	5023
Compressed air store (CAES underground tank)	2155	289	2444	1579
Liquefied air store (LAES above-ground tank)	5305	229	5534	5299
Hydrogen store (HESFC with a fuel cell)	6675	707	7382	6517
Hydrogen store (HESFC with a gas turbine)	8950	820	9770	8905
Unit cost of undelivered electric energy: scheduled limitations (k_{nep})-unplanned-emergency limitations (k_{nea})			7500–13,500	

Considering the actual conditions of the power system operation, the actual time of using energy stores for the needs of power balancing services is different each year. For this reason, for optimization studies it is useful to prepare a graph showing the dependence of the net unit costs of power balancing with energy stores on the time of their use in a year. This dependence for the data presented in Table 3 is presented in Figure 6.

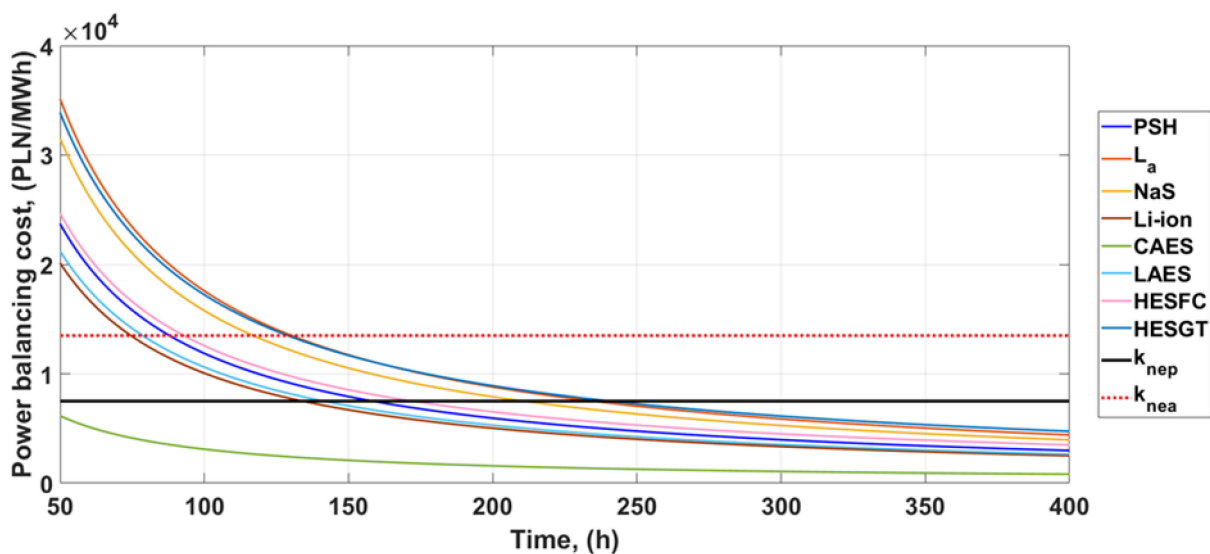


Figure 6. Dependence of the net unit power balancing cost by energy storages on the time of their use in a year (prepared by the author).

Energy storage plants should be taken into account by TSO as one of possible solutions to optimize the development and operation of PS, including for KSE peak power balancing. In the nearest future, the actual potential for the effective use of energy stores is related to pumped storage power plants, various types of batteries, compressed and liquefied air stores and hydrogen plants [17–19]. The assessment of the effectiveness of acquiring new energy storage solutions for peak power balancing on the market can be made on the basis of an analysis of the unit power balancing costs.

6. Results of the Analyses and Discussion

Based on the analyses presented in items 2–5 and the performed calculations for KSE, it is necessary to make a collective comparison of the various options for balancing power systems' peak power. In order to make a representative selection from among all the earlier analyzed variants, the criteria of market availability, economic attractiveness and technology development prospects in this area have been taken into consideration. To this end, the following have been adopted for further studies:

- system services group:
 1. emergency cold reserve service-being a result of public tenders conducted by TSO (IRZ), which were similar in nature to the operator's strategic reserve mechanisms also applied by other TSOs,
 2. reduction in demand at the operator's request (DSRwyk) the cost of which is based on the mechanism of payment for its actual utilization binding in the first tenders,
 3. reduction in demand at the operator's request (DSRrm) the cost of which is based on the power market mechanism implemented in KSE, and the resulting rates for the readiness to render this service averaged for the years 2021–2024, being a result of the four power auctions conducted in the period 2018–2019 [20],
 4. emergency operation of a new generation source dedicated for peak operation, oil fuel powered (ZISno), the cost of which has been calculated for the averaged prices of this fuel valid in 2019,
- group of trans-border connections:
 1. on the basis of the data presented in Table 2, one value has been adopted, being average costs from items 2–4, which, as a good approximation, correspond to the costs of construction and operation of new trans-border connections (PTn) estimated in 2020,
- energy stores group:
 - a. pumped storage power plant (PSH),
 - b. lithium-ion (Li-ion) battery,
 - c. compressed air store (CAES),
 - d. liquefied air store (LAES),
 - e. hydrogen store with a fuel cell (HESFC).

It should be emphasized that for the above mentioned peak power balancing solutions an update was made for the year 2020, which has resulted in the need to make repeated calculations for electric energy and gas prices valid in 2019 being the subject matter of the transactions on TGE and RB and the binding rates for the operating power reserve (ORM). A comparison of the net unit power balancing costs of selected KSE peak power sources, for different times of their utilization in a year, is presented in Figure 7.

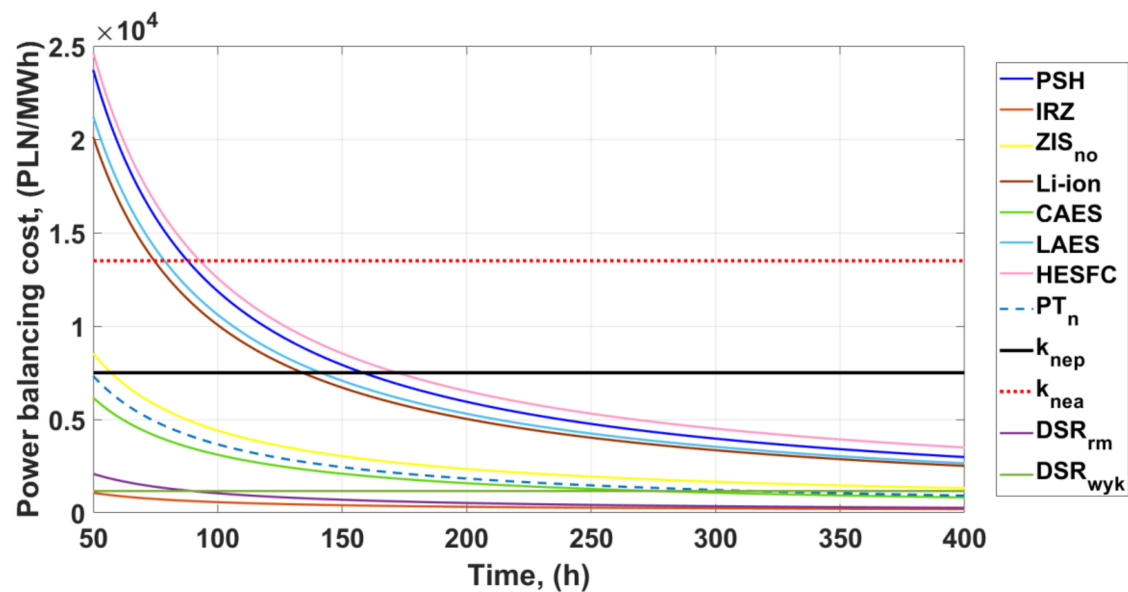


Figure 7. Comparison of the net unit power balancing cost by selected KSE peak power sources, for different times of their utilization in a year (prepared by the author for 2020).

One of the most effective tools of market-based impact of transmission and distribution system operators and energy vendors on the end users is demand side response. This solution should be effectively used for the purposes of balancing PS peak loads [21].

TSOs should carefully analyze and take advantage of the opportunities that are offered by the mechanisms of the so-called operator's strategic reserve. A good example is the emergency cold reserve service, being a result of public tenders conducted by TSO.

A very attractive solution in the group of energy storage plants are compressed air stores. These solutions is characterized by a relatively low unit cost and the capacity to generate power even during the whole so-called day zone. The capacity of such stores allows TSOs to reduce expenses on ensuring the required operating reserve.

Quite good assessment results are also achieved by oil fuel powered emergency sources dedicated for peak operation. These sources, in spite of having slightly higher unit power balancing costs than some other solutions being compared, are characterized by much better performance parameters.

The utilization of trans-border connections constitutes an important element in building KSE's energy security. Assuming that their construction is frequently determined by the criterion of ensuring access to cheaper energy to the end users, their cost attractiveness is much higher than resulting directly from the data presented in Figure 7.

We should expect that the economic attractiveness of utilizing battery-powered energy stores will be growing in the future. Liquefied air stores are slightly worse in these terms, but they can also be perceived as an important source of peak power.

Energy storage in new pumped storage power plants is in the group of the most expensive solutions, regardless of the time of using peak power in a year (100–400 h). This is determined by a high unit investment cost, including in particular that of the hydroengineering structures required for this type of solutions.

Peak power balancing using hydrogen-to-electric energy generation, storage and processing plants is a very attractive solution for TSOs from the point of view of the technical parameters. The possibilities of economic utilization of this technology will be growing along with a further reduction in unit construction costs of particular links in the energy processing chain.

In order to make the aforementioned conclusions objective, a sensitivity analysis has also been made of the key factors determining the level of power balancing costs. Under this analysis, an examination has been made in particular of the impact of changes in electric energy, gas and fuel oil prices on wholesale markets, capital expenditures sustained

on the construction of the power sources being analyzed and the efficiency of energy processing. The results of this analysis have confirmed the formulated conclusions. System services, including DSR and IRZ, remain competitive as compared to other solutions. In fact, the purchase price of the services is determined by its comparison to the costs of other power sources, requiring significant construction-related investment expenses to be sustained. Changes in the competitive position of battery-powered energy stores, hydrogen and liquefied air stores are possible only provided that these stores' unit investment outlays are significantly reduced, by at least 50%. It results from the fact that variable costs resulting from energy prices and the efficiency of these systems affect the total costs in the same way as in the case of the other solutions being compared.

7. Conclusions

As a result of the conducted studies of KSE operation, regarding the prospects for its operation in the upcoming decade or so, the following conclusions and observations can be made:

- KSE's power balance analyses until 2030 performed by the authors [12], taking account of the plans to build and liquidate generating units as well as the growing demand for power from the end users indicate that, depending on the adopted option of withdrawal of old generating units from operation, no later than the period 2022–2024 we should expect difficulties in covering KSE's power demand, in particular in peak load periods,
- considering the fact that TSO has limited peak power sources and the other services such as: generation forced by system considerations, work with overload as well as operators' import of electric energy do not meet the criterion of their availability, it should be stated that the needs of TSO are not satisfied as necessary. Such a situation must be regarded as incorrect and requires to be urgently changed,
- the estimation study of the direct financial effects of the limitations in electric energy supply and consumption for the end users connected to KSE arising in recent years indicates that the unit costs of undelivered energy at the level from 7500 PLN/MWh for scheduled limitations to 13,500 PLN/MWh for emergency limitations, demonstrates an urgent need to implement effective solutions in order to balance KSE needs,
- there are two basic groups within the group of DSR mechanisms used for KSE power balancing. In the first of them, the end user is remunerated only for making use of their flexibility, while in the second one the payment involves their readiness to render the flexible demand service. The economic effectiveness of both solutions depends on the actual utilization time in a year. TSO's should accurately forecast the degree of use of the DSR mechanism and on this basis select an adequate method of remunerating the service providers. This approach is necessary to avoid unjustified system operating costs, overburdening end-users,
- the scope of the possible solutions as well as the potential for load reduction on the side of the end users is however much broader, meaning that it should be particularly interest to market regulators. It is necessary, for example, to introduce a mandatory and general mechanism of multi-zone tariffs, dynamic tariffs, which are an element of real-time pricing,
- TSOs should carefully analyze and take advantage of the opportunities that are offered by the mechanisms of the so-called operator's strategic reserve. They do not essentially disturb the operation of the market mechanisms, and at the same time they are effective peak power balancing solutions in the interim period, i.e., until the missing peak power is supplemented by market mechanisms. This solution should be the subject to unification of the rules for their application within the framework of the mechanisms of building well integrated internal energy market. The various mechanisms for maintaining reserve generation capacity currently used in this area in the EU, such as capacity market, strategic reserve, operator's reserve and contract for differences, are not conducive to building a competitive energy market,

- on the basis of the available data concerning technical-economic parameters, the selected economic and non-economic criteria of the technologies being compared and after conducting comparative analyses of the various options for balancing power at peak loads, it can be concluded that compressed air stores are a competitive group of solutions that should be taken into account in the decision-making process regarding supplementation of the currently used solutions. Along with the development of this technology towards adiabatic circuits, increasing plant efficiency, their economic efficiency will be further improved. Such energy storage may additionally contribute to increase the integration of renewable energy sources with the power system. This solution should be included in the group of technologies covered by uniform competitive mechanisms to support energy security processes,
- quite good results of the comparative assessment are obtained by emergency sources dedicated for peak operation, gas or oil fuel powered, according to local technical and economic conditions. Their most important utility values are: high reliability and flexibility of operation, short construction time, easy operation, making them stand out in the case of a lower importance of the unit cost criterion,
- the utilization of trans-border connections constitutes an important element in building energy security. The weaknesses of this source is limited reliability of power availability in the conditions of the simultaneous presence of problems with PS balancing at the neighboring TSOs. However, trans-border lines can significantly contribute to building a competitive electric energy market, as they are used at the time of the systems' normal operation, and not just as an emergency solution. Therefore, compliance by EU Member States with normative indicators in terms of the capacity of trans-border connections should be treated with due diligence,
- batteries have the potential to be more widely used for peak power balancing. Their presently limited role is determined by high unit investment expenses, a dynamic growth of new, cheaper and more effective technologies taking place on the market will cause a breakthrough in this area. This is confirmed by more widespread utilization of batteries for different purposes related to maintenance of the power system's required working parameters. Batteries, due to their ease of installation and the resulting possibility of their dispersion in the power system, can have a large impact on the absorption of energy from renewable sources, especially those that are not controllable. This solution should be included in the group of technologies covered by uniform competitive mechanisms supporting their financing and development,
- energy storage in pumped storage power plants is ranked lowest in the assessed group, regardless of the peak power utilization in a year (100–400 h). This solution is characterized by the highest unit power balancing costs, making the total evaluation, in spite of the obtained highest scores for other important non-cost criteria, the lowest within quite a broad range of changes in the weight of the unit cost criterion. These power plants, also for environmental reasons, although they currently constitute an essential part of energy storage installations, will not play a significant role in the group of new ones,
- energy storage using hydrogen plants will become competitive against other solutions being compared in the future. It will be so only provided that the unit investment expenses, concerning in particular electrolyzers, fuel cells, and gas turbines, are significantly reduced. Another important issue is also further improvement in the efficiency of energy processing. It will be fostered by fast development of mobility utilizing hydrogen produced with the use of electric energy generated in renewable energy sources as observed worldwide. In this regard, it is necessary to urgently and commonly adopt a strategy for the development of their hydrogen economy in the Member States and its consistent implementation. Hydrogen is a fuel that is not only suitable for balancing peak power, but is also a way to reduce greenhouse gas emissions from industry, transport, electricity, heat and cold production,

- the traditional approach, limited, in the process of assessment of different peak power balancing solutions, to the analysis of the costs of electric energy generation, can be insufficient to make rational decisions in these areas. In such cases the multiple-criteria analysis should be helpful, under which non-economic criteria should be taken into account apart from the economic criterion, including in particular: power source flexibility, its market availability, reliability of power disposal by TSO as well as compliance of the technology with the principles of sustainable development. This tool may be a good basis for making decisions by the entities responsible for energy safety.

Author Contributions: Conceptualization, H.M. and M.K.; methodology, H.M.; validation, H.M. and M.K.; formal analysis, H.M.; data curation, H.M.; writing—original draft preparation, H.M.; writing—review and editing, M.K.; visualization, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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