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Assessment of energy storage for energy strategies development on a regional scale

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Abstract

The article aims to develop an optimisation model for power sector development and propose the desired direction of using energy storage technologies in the analysed period to distribution system operators (DSO) to develop renewable energy on a regional and local scale. The article presents the results of research on various types of energy storage technologies that can be used in the distribution system, such as a reservoir with EDLC (Electric Double-Layer Capacitors) supercapacitors, a reservoir with LIC (Lithium-Ion Capacitor) supercapacitors, a reservoir with LFP (Lithium Ferro) batteries. Phosphate LiFe PO4), a container with LTO (Lithium Titanate Oxide) batteries and a container with VRLA (Valve Regulated Lead Acid) batteries. It should be emphasised that due to the continuously more frequent problems with increased fluctuations in active power in distribution networks, the proposed model for optimising the use of electricity is an important approach to the rationalisation of actions and decisions made by distribution network operators (DSO). The research undertaken contributes to the development of knowledge concerning low carbon energy transition, as well as the energy storage subsystem.

Keywords

Regional energy planning; low carbon energy transition; renewable energy; energy storage

Introduction

The development of technical solutions based on energy storage technology ensuring innovative system services may be a response to new challenges for distribution network operators (DSO). One of the solutions used locally, and increasing the quality and efficiency of electricity use in low voltage distribution networks, is the use of electricity storage to provide system services. The use of energy storage counteracts the risks related to the increasing share of new types of loads on the electricity market, related to the development of electromobility (Zagrajek et al., 2020) and renewable energy sources (Eltawilet al., 2010; Yao et al., 2020). Provision of innovative system services requires the use of modern power electronic converters as controlling actuators. Modern power grids are threatened by the increased number of dispersed, small energy sources with high variability of generated power (PV, wind), which may locally affect the voltage profile of the grid (Khaboot et al., 2019; Potter et al., 2018). This is of particular importance for DSOs, which are energy distributing companies that supply energy to their customers. They are responsible for network traffic in the distribution system, current and long-term functional security of the system, operation, maintenance, overhauls and the necessary development of the distribution network (Hydro Tasmania 2018 and The Energy Law 1997 and Chakraborty et al., 2020). In addition, DSOs have a legal obligation to connect all customers who meet technical requirements to the distribution network. The term DSO describes both a natural and a legal person responsible for the operation and maintenance and, if necessary, for the development of the distribution system (Lyon Group, 2018), connections with other systems and ensuring the long-term ability of the system to meet the justified requirements of electricity distribution (Wojciechowski 2016; Namysłowska-Wilczyńska, et al., 2016; Mirek, 2016).

The article presents the results of the research obtained as part of the research and development project (European Union Directive 2003 and Abedin, Rosen 2011) and extends the knowledge generated in these studies. The article also attempts to answer research questions such as:

- what is the future of the domestic energy industry,
- what kind of energy is to come from Renewable Energy Sources (RES),
- what future transmission infrastructure is necessary for energy storage,
- which field-proven scientific methods can be useful in planning energy production and building a renewable energy scenario at the local level.

This paper aims to develop and test strategies and methods, including business ones, for the use of energy storage in electricity networks to improve the quality and efficiency of electricity use and to develop a product proposal for customers. The research focused on different types of energy storage technologies that may appear in the system, namely:

- EDLC (Electric Double-Layer Capacitors) supercapacitor storage,
- tray with LIC (Lithium-Ion Capacitor) supercapacitors,
- tray with LFP batteries (Lithium Ferro Phosphate LiFePO4),
- tray with LTO batteries (LithiumTitanate Oxide),
- VRLA (Valve Regulated Lead Acid batteries

The results of the research are presented in the first part of the article and form the basis for the development of a model for optimising the use of electricity, taking into account various types of energy storage technologies that can be used in the energy distribution system, which is shown in the second part of the article.

Due to the availability and technical feasibility of using selected electricity storage devices, it is therefore important to develop a distribution network development model that takes into account various types of energy storage technologies (Wojciechowski, 2008; Parau et al., 2014). The presented model contributes to supporting DSO decision-making processes in order to provide innovative system services, support the reliability and development of the distribution network, and can also be used to create energy policy by the State, the European Union (Pavlov and Olesen, 2011; Sunliang, 2010; Ercan and Ataer, 2006). So far, there have not been any studies in the literature on an autonomous model of regional energy systems based on the competition of individual renewable energy sources using various available electricity storage technologies.

The model includes renewable energy sources, which means that it can also be used by local government units to support a low-emission economy and to create assumptions in stimulating regional and local development. The conducted research contributes to the development of knowledge concerning alternative energy sources in the power sector, as well as the energy storage subsystem.

Characteristics of storage technologies for applications in low voltage distribution networks

Currently, in power systems, energy storage is used for two basic types of activities, i.e. improving the quality of energy supply (including improving the quality of voltage parameters and reducing the impact of loads and unsteady sources on these parameters) and generally understood energy flow management (Lezynski et al., 2019;

Jarnut et al., 2017; Hameer et al., 2015). Although the boundary between these types of activities is not clear, in both cases, different dimensions of the reservoir parameters and a different selection of its technology have been adopted (Paska et al., 2005; Kafejko, 2004). Among the currently known energy storage technologies, the greatest possible applications in LV distribution systems are electrochemical battery accumulators, electrostatic supercapacitor accumulators and hybrid accumulators combining the properties of both technologies in their structure (Bronk, Czarnecki 2013 and Johnson 2011). These types of cartridges are currently at an advanced stage of development and are available on the market in multiple variants. They are designed as multi-cell storage units built of single cells or modules for stationary applications. This facilitates their scaling and enables their implementation practically anywhere in the distribution system (Eyer and Corey, 2010; Okafor, 2010; Vikelgaard, 2012).

Locations, energy properties and operating conditions of storage tanks

Two technologies are currently dominant among electrochemical reservoirs: the first one - leaving the market, but still unrivalled in terms of investment - LeadAcid (LA) type acid technology, and the second technology - LithiumIon (Li-Ion), which is still slightly more expensive in terms of investments (Amirante et al., 2015; Jamrozik and Tutak, 2011). The remaining technologies, although dynamically developed, do not dominate the market to the same extent as the two mentioned. This is related, for example, to the specific operating conditions of high-temperature NaS storage (temperature above 300°C) or the location requirements of flow storage tanks (low mass and volume density, narrow operating temperature range), which predisposes them to use in large-scale energy storage systems (Szwaja et al., 2013; Badyta and Milewski 2010; Tomczyk, 2011). Location requirements related to limited space (potential applications in indoor substations) and mass (potential applications in pole stations) particularly indicate lithium technology as one that has a chance of broader application in low voltage distribution networks or MV / LV stations (Akhil et al., 2013; Deaf et al., 2013).

When locating electrochemical storage tanks, special attention is also paid to the safety requirements during the operation of this type of storage tanks related to the potential emission of toxic or flammable gases, especially during the charging processes. For this reason, in order to minimise the risk of fire, among the acid technologies in stationary applications, the most frequently used are "sealed" batteries of the Valve Regulated Lead Acid (VRLA) type with a gel electrolyte (Gel) or electrolyte trapped in a glass mat (Absorbent Glass Mat - AGM), which characterise low gas emission, which also reduces the ventilation requirements of battery cabinets. Moreover, the VRLA acid batteries, unlike the wet FLA type batteries, can operate in any position (Jung et al., 2019).

Lithium batteries are free from gas emissions under normal operating conditions. In their case, the degree of fire risk in the event of damage to the outer coating of the cell or monoblock determines the choice of a specific lithium technology in terms of safety (Bednarek, Kasprzyk, 2012; Wit et al., 2000). The safest cells are lithium-iron (Lithium Iron Phosphate - LiFe PO4 or LFP) and lithium-titanium (Lithium Titanium Oxide - LTO). For this reason, they are more common than, for example, lithium cells of the NMC or NCA type. The list of location parameters of storage tanks in washed-out technologies based on the conducted research is presented in Tab. 1.

Table 1. List of storage tank location parameters in selected technologies

Storage type	Capacity of the module/cell [Wh]	External dimensions [mm]	Weight [kg]	Volume [m^3]	Mass energy density [Wh/kg]	Energy bulk density [kWh/m^3]
VRLA 12V/136Ah	1632	329x173x209	31,5	0,012	51,8	136
LiFePO4 3,2V/100Ah	320	221x142x61	3,1	0,002	103,2	160
LTO 2,4V/30Ah	72	235x135x29	1,59	0,00092	45,3	78,3
EDLC 48V/166F	53,1	430x200x182	16	0,0156	3,32	3,4
LIC 45V/275F	52,8	260x167x140	5,6	0,0061	9,43	8,6

Source: own study.

All electrochemical accumulators are characterised by limited charging / discharging dynamics, defined by the Crate index, mainly related to the limited active surface of the electrodes, while the charging process is more critical, which means that the permissible charging current of electrochemical cells is two or even three times lower than the permissible discharge current (Skoczkowski et al., 2016; Skoczkowski and Bielecki 2016; Hasse, 2016). The best in terms of the dynamics of cyclic charging / discharging are LTO, NCA and LiFePO4 lithium cells (the worst of the mentioned 1C / 3C). Acid cells are much worse in this respect (the best VRLA 0.5C / 0.5C). The cyclic operation of electrochemical accumulators at critical values of charging/discharging currents is one of the factors that affect the lifetime of cells and the efficiency of energy storage processes (Zhumabekuly and

Svetinovic, 2016; Boucher et al., 2017). For this reason, the recommended values of the charge/discharge currents at which the cell cycle life is determined are usually twice less than the critical values. The second factor influencing the cyclical life of the hoppers is the Depth of Discharge (DOD). For VRLA batteries, the recommended maximum DOD is 50%. This ensures a VRLA battery life of 1000 cycles. In the case of lithium batteries, these values with the permissible DOD equal to 80% are, respectively: approx. 3000 cycles for LiFePO4, approx. 20,000 cycles for LTO (Hwang et al., 2017; Mengelkamp et al., 2018; Jarnut et al., 2017).

In electrochemical battery discharge processes, the critical parameters are maximum current and final discharge voltage occurring at the permissible DOD (Zhumabekuly, Svetinovic 2016). While in the case of lithium cells, the constant voltage phase (absorption or saturation phase) is not required and is associated only with not using the full capacity of the battery, which paradoxically increases the battery life, in the case of VRLA cells, the notorious omission of this phase results in rapid degradation of the battery. This means that lithium storage should be used in services where it is required to work with a constant set value of current or power in both directions of energy flow (Bujło 2010).

In multi-cell accumulators where the cells are connected in series (in chains) to obtain high operating voltage, there is a risk of uneven charging of the cells and uneven distribution of potentials inside each of the chains (Rabe et al., 2019). The list of energy properties and operating parameters of storage tanks in washed-out technologies based on the tests performed are presented in Tabs. 2 and 3.

Table 2. List of energy properties of storage tanks in selected technologies

Store type	Internal resistance (ESR) [mΩ]	Storage efficiency (η_N) [%]	The degree of self-discharge [% / month]	Depth of discharge (DOD) [%]	Cyclic life (NC (DOD)) [cycle]	Calendar life [patch]
VRLA	> 5	< 85	> 2	50	< 1 000	< 10
LiFePO4	< 1	> 96	< 5	80	> 3 000	> 10
LTO	< 1	> 96	< 3	80	> 20 000	> 10
EDLC	< 3	> 96	> 10	75	1 mln	> 10
LIC	< 2	> 96	< 2	100	2 mln	> 15

Source: own study

Table 3. List of operational parameters of storage tanks in selected technologies

Storage type	Nominal voltage [V]	Maximum voltage [V]	Minimum voltage [V]	Maximum charging current [1 / h]	Maximum discharge current [1 / h]	Working temperature range [° C]
VRLA	12	13,8	10,5	0,5C	0,5C	- 20 ÷ 50
LiFePO4	3,2	3,65	2,8	2C	3C	- 20 ÷ 55
LTO	2,4	2,75	1,85	6C	15C	- 25 ÷ 55
EDLC	48	51,3	0	900C	900C	- 24 ÷ 65
LIC	45	45,6	26,4	320C	320C	- 20 ÷ 70

Source: own study

Operational properties of energy storage devices made in selected technologies - summary of research results

The conducted experimental studies and the analysis of the parameters of catalogue energy storage devices made in the technologies selected for the research allow for the comparison of their properties and the formulation of conclusions regarding their potential use and operation in stationary systems cooperating with the distribution network. A synthetic summary of these studies is presented in the tab. 4.

Table 4. Summary of operational properties of storage tanks in selected technologies

Storage type	Constant current charging mode (CC)	Constant voltage charging mode (CV)	Maintenance charging	Voltage equalisation system
VRLA	Yes, until the absorption phase voltage is reached (below the gassing voltage), state of charge after the CC phase is about 70% of the nominal capacity	Yes, until the charging current drops to 3%, at an absorption voltage of 14.3V	Yes, at constant, reduced voltage to the recommended voltage of the float phase of 13.8V	This is not required
LiFePO4	Yes, until the saturation voltage of 3.65V is reached, the state of charge after the CC phase is about 80% of the nominal capacity	Yes, until the charging current drops to 5-10% at a saturation voltage of 3.65V Note: Higher saturation voltages achieve an increase in capacitance but significantly shorten the service life	This is not required	It is absolutely necessary to activate the balancer and equalise the voltages periodically; you should trigger the CV charging mode
LTO	Yes, until a saturation voltage of 2.6V is reached	Yes, until the charging current drops to 5-10% at a	This is not required	It is absolutely necessary to activate the balancer and

	the state of charge after the CC phase is about 80% of the nominal capacity	saturation voltage of 2.6V Note: Higher saturation voltages achieve an increase in capacitance but significantly shorten the service life		equalise the voltages periodically; you should trigger the CV charging mode
EDLC	Yes, until a saturation voltage of 2.5V is achieved	This is not required	Recommended due to the high level of self-discharge	Absolutely required
LIC	Yes, until a saturation voltage of 45.6V is reached; the state of charge after the CC phase is about 90% of the rated capacity	This is not required	This is not required	It is absolutely necessary to activate the balancer and equalise the voltages periodically; you should trigger the CV charging mode

Source: own study

Model of energy development in the West Pomeranian Voivodeship taking into account the use of selected technologies of electricity storage in the LV distribution network

The systemic approach assumes that the studied reality is too complex to be fully known. Therefore, the postulates replacing the examined, complex object with its model, i.e. simplified images of economic reality, where the use of simplifications results from the complex nature of economic phenomena, and the deliberate omission of certain relations allows focusing on a selected phenomenon

To solve the model, linear and non-linear programming methods, dynamic programming, probability theory, game theory, mathematical statistics, etc. There are many types of decision models, depending on the decision making results and the type of decision problem.

The use of decision models in the approach to energy management issues allows for the formulation of a number of methods and system solutions.

The decision is very often a random or purely intuitive one, not supported by any analyses or strategy planning. In order to avoid errors and randomness in the selection, criteria and objectives for action must be established before planning the energy model of the area under study. Therefore, the goals can be of a different nature:

- competitive goal - when increasing the value of one of the goals reduces the achievement of the other, e.g. maximising profit and increasing the size of its risk,
- linked objectives, between which there is a relationship that progresses towards one objective is accompanied by an increase in the other,
- complementary goals that support each other,
- supplementary goals - independent of each other, reducing or increasing the accomplishment of one does not affect the size of the other goal.

The described relationships between individual goals are not permanent. Some of them may go into the other, depending on the size of the absolute production for renewable energy and the energy storage used. The goals can also be complementary, i.e. complement each other in the use of one production factor and at the same time compete with each other for another factor.

The nature of the relationship between the various criteria is difficult to establish. Their formation can be observed only in the process of optimising the mathematical model of the energy production plan in a given area. The task in planning the model is to construct a production plan that would maximally achieve individual goals in accordance with his preferences.

Therefore, when planning energy production, it is necessary to refer to scientifically proven methods. These include multi-criteria methods.

The article proposes an original energy development model in the West Pomeranian Voivodeship with energy storage, taking into account various types of technologies that may appear in the distribution system. Using an optimisation multi-criteria model, a model was developed to optimise the regional energy potential, considering selected electricity storage technologies for use in LV distribution networks.

A properly constructed model of the energy sector development in the West Pomeranian Province includes the data defining the parameters of the mathematical model, such as

quantities characterising a given decision-making situation - determined at the stage of identification of the research objective,

- decision variables - unknowns, determined during the decision-making process, whose numerical value is conditioned by the set of constraints and the value of the objective function,

- the constraint conditions - a system of constraints defining the decision space presented in the form of a set of acceptable solutions,

- objective function defined as an indicator of solution quality assessment - a function strictly dependent on the value of decision variables.

For the purpose of analysing the interactions of the alternatives, it is necessary to develop such a mathematical model, which considers the dependencies between the individual elements of the model.

Planned events are n important element of the decision-making model, i.e. forecasts of energy production from conventional and renewable sources. Often, the needs for energy production from conventional and renewable sources are contradictory. Therefore, to obtain a compromise, apart from the selection of appropriate indicators, which are partial criteria of a multi-criteria optimisation task, it is also necessary to adopt certain constraints conditioning the acceptance of the obtained solution.

In addition, the following groups of constraints have been adopted in the developed model, related to costs and to the loss of soil fertility caused by the production of energy resources. The model takes into account forecasts of EUA prices in 2021-2030.

In the case of the energy development model in the West Pomeranian Region, the aim is to determine an optimal solution for which the multi-criteria objective function reaches an extreme value. In reality, however, there is rarely a situation when an optimal solution exists due to all the evaluation criteria. Therefore, a compromise solution becomes satisfactory. Most often, it is an efficient or non-dominated solution, also called pareto-optimal solution.

The West Pomeranian Province was chosen as the research object, and the time range of the empirical research was set to 2018-2030.

Working conditions of the bunker system elements in the implementation of the most important system services

Considering the characteristics of disturbances in the LV distribution network, as well as the list of technical properties and operational requirements in selected technologies. Based on the research carried out, Tab. 5 lists the requirements for energy conditioning systems equipped with energy storage and installed in LV networks for the implementation of individual types of system services.

Table 5. Summary of the operating conditions of the storage system components for the provision of system services in the LV distribution network

Type of service/control strategy	**Requirements for the line converter**		**Requirements for the storage converter**		**Preferred storage technology**
	functionality	**algorithm**	**functionality**	**algorithm**	
Active power stabilisation	Fast active power regulation	Reduction of power fluctuations in the PCC (on the substation side); P power control on the AC side, including SOC controlΔDirect P /	Voltage stabilisation in DClink	SOC, alarms and security	EDLC, LIC, LFP, LTO Parameters based on measurements and the developed selection method
Peak power reduction (power guard)	Fast power adjustment	Power limitation in PCC (substation side) at a fixed level Direct AC power P / Pmax control, including SOC control	Voltage stabilisation in DClink	SOC, alarms and security	LFP, LTO Parameters based on measurements and the developed selection method
DSM including power reduction on demand	Slow active power regulation	Limiting or increasing the power at the PCC (substation side) at a fixed level	Voltage stabilisation in DClink	SOC, alarms and security	LFP, LTO, VRLA Parameters based on measurements and the developed selection method
Voltage stabilisation deep in the LV network	Quick adjustment of active and reactive power *	Direct control of active and reactive power on the AC side according to P / V and Q / V, including SOC control	Voltage stabilisation in DClink	SOC, alarms and security	EDLC, LIC, LFP, LTO Parameters based on measurements and the developed selection method
Voltage regulation in a substation	Reactive and active power regulation *	Direct regulation of reactive and active power on the AC side according to Q / V and P / V, including SOC control	Voltage stabilisation in DClink	SOC, alarms and security	No preference, no tray required

Type of service/control strategy	**Requirements for the line converter**		**Requirements for the storage converter**		**Preferred storage technology**
	functionality	**algorithm**	**functionality**	**algorithm**	
Voltage regulation downstream of the LV network	Active power regulation	Direct control of active and reactive power on the AC side according to P / V and Q / V, including SOC control	Voltage stabilisation in DClink	SOC, alarms and security	LFP, LTO, VRLA Parameters based on measurements and the developed selection method

Source: own study

The model selects five types of system services to be performed with the use of energy storage:
Service 1: stabilisation of RES capacities;
Service 2: voltage regulation with active and reactive power;
Service 3: reactive power and distortion compensation;
Service 4: stabilisation of the power of restless receivers;
Service 5: on-demand power reduction.

Predispositions to implement individual services with the use of a specific technology are summarised in the tab. 6.

Table 6. Possibility of providing a system service by a given electricity storage technology

Service Tray type	**Compensation of reactive power and distortions**	**Stabilisation of RES capacities**	**Stabilisation of uninterrupted loads**	**Voltage regulation with active and reactive power**	**Power reduction on demand**
EDLC	+	+	+	-	-
LIC	+	+	+	-	-
LiFePO4	+	+	+	+	+
LTO	+	+	+	+	+
VRLA	+	-	-	+	+

Source: own study

Costs of energy storage in the tested storage tanks

One of the basic issues related to the use of energy storage to optimise the cost-effective operation of prosumer systems is determining the cost of energy storage. This cost should take into account both the investment cost for a given technology and the service life. Battery life depends on the degree of cyclic discharge; therefore, this fact should also be taken into account. The cost of storing energy in the reservoir can be determined from the simplified formula:

$$K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} \qquad (1)$$

where:
K_{ES} - the cost of energy storage [PLN / kWh];
K_I - investment cost;
C_N (kWh) - rated battery capacity [kWh];
$N_{ES\,(DOD)}$ - battery life [cycles] at the average value of the degree of cyclic discharge;
DOD - mean degree of cyclic discharge [0 - 1];
In the case of the tested MWL 40-12 batteries, the cost of energy storage in acid batteries (VRLA) will be:

$$K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} = \frac{334[PLN]}{0{,}5 \cdot 500 \cdot 0{,}48[kWh]} = 2{,}78[PLN/kWh] K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} = \frac{334[PLN]}{0{,}5 \cdot 500 \cdot 0{,}48[kWh]} = 2{,}78[PLN/kWh]$$

The investment cost of the MWL 40-12 type batteries related to the usable capacity in cyclic operation:

$$K_{ES} = \frac{K_I}{DOD \cdot C_{N(kWh)}} = \frac{334[PLN]}{0{,}5 \cdot 0{,}48[kWh]} = 1391[PLN/kWh]$$

Energy storage devices based on acid batteries (VRLA) are characterised by a relatively low investment cost (less than PLN 1,000 / kWh). Unfortunately, this technology is not without its drawbacks. The cost of energy storage, taken into account when estimating the costs of providing power control services in systems with energy storage, largely depends on the storage life, which in turn depends on the degree of cyclical discharge. In acid technology, it is rare to find batteries with a service life of more than 1000 cycles with a DOD depth of cyclic discharge above 50%. With this DOD value, they usually have a service life of approx. 500 cycles, which means that the storage costs increase and exceed the value of PLN 2.5 / kWh.

In the case of the tested LiFePO4 storage tanks with a BMS system, the cost of energy storage will be:

$$K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} = \frac{6600[PLN]}{0{,}8 \cdot 2 \cdot 10^3 \cdot 1{,}024[kWh]} = 4{,}03[PLN/kWh]$$

The investment cost of the LiFePO4 storage tank with a capacity of 1.024 kWh related to its rated capacity in the case of the tested battery is:

Battery storages with LiFePO4 cells are characterised by a low internal resistance, which predisposes them to work in systems for dynamic reduction of output power fluctuations of renewable energy micro-sources. The high investment cost (approx. PLN 4,545 / kWh) is partly compensated by the very high lifetime of the storage tank (approx. 2000 cycles according to the manufacturer). The main advantage of LiFePO4 storage tanks in relation to acid batteries is the higher value of the DOD cyclic discharge rate (80% in lithium-iron compared to 50% in acid batteries). These batteries also have more than twice the lifetime, which means that despite the higher investment costs, their operation is cheaper than the batteries made with acid technology.

In the case of the tested LTO storage tanks, the cost of energy storage for 1C current will be:

$$K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} = \frac{250[PLN]}{0{,}8 \cdot 20 \cdot 10^3 \cdot 72[Wh]} = 0{,}22[PLN/kWh]$$

The calculations took into account the investment cost of the LTO storage tank with a capacity of 72 Wh:

Battery accumulators with LTO cells are characterised by a low internal resistance, which predisposes them to work in systems for dynamic reduction of output power fluctuations of renewable energy micro-sources and systems with high dynamics of load power changes. The high investment cost (approx. PLN 5,069 / kWh) is partly compensated by the very high lifetime of the storage tank (approx. 20,000 cycles according to the manufacturer), which is the main advantage of LTO storage tanks compared to other lithium and acid technologies.

In the case of the tested EDLC storage tanks built on the basis of JSR Ultimo prismatic cells, the cost of energy storage will be:

$$K_{ES} = \frac{K_I}{N_{ES(DOD)} \cdot C_{N(kWh)}} = \frac{24000[PLN]}{1 \cdot 10^6 \cdot 0{,}140[kWh]} = 0{,}17[PLN/kWh]$$

The investment cost of the EDLC storage tank related to its rated capacity in the case of the tested battery:

$$K_{I(kWh)} = \frac{K_I}{C_{N(kWh)}} = \frac{24000[PLN]}{0{,}140[kWh]} \cong 171428{,}6[PLN/kWh]$$

EDLC supercapacitors are characterised by a low internal resistance, which predisposes them to work in systems for dynamic reduction of output power fluctuations of renewable energy micro-sources. The high investment cost (approx. PLN 171,000 / kWh) is partly compensated by the very long service life of the storage tank (approx. 1 million cycles, according to the manufacturer). The main disadvantage of EDLC reservoirs compared to LIC supercapacitors is a much wider voltage range (approx. 40% of the LIC rated voltage in relation to 100% of the EDLC rated voltage) of operation, which guarantees full use of the store energy. When designing converter systems connecting the energy storage with the network interface, where due to the reduction of the cost of power electronic components on the lower voltage side (from the storage side), the voltage and current transformation ratio is reduced, this means that it is not possible to use the entire energy of the storage and increases the cost of energy storage.

In the case of the tested LICs built on JSR Ultimo prismatic cells, the cost of energy storage will be:

$$K_{ES} = \frac{K_I}{DOD \cdot N_{ES(DOD)} \cdot C_{N(kWh)}} = \frac{24000[PLN]}{1 \cdot 1 \cdot 10^6 \cdot 0{,}158[kWh]} = 0{,}15[PLN/kWh]$$

The investment cost of the LIC storage tank concerning its rated capacity in the case of the tested battery is:

$$K_{I(kWh)} = \frac{K_I}{C_{N(kWh)}} = \frac{24000[PLN]}{0,158[kWh]} \cong 152000[PLN/kWh]$$

LIC supercapacitor storage tanks are characterised by a low internal resistance, which makes them suitable for use in systems for dynamic reduction of output power fluctuations from renewable energy sources. The high investment cost (approx. PLN 152,000 / kWh) is partially compensated by the very high lifetime of the storage (approx. 1 million cycles, according to the manufacturer). Tab. 7 presents a synthetic summary of the designated investment and operating costs of reservoirs made in selected technologies.

Table 7. List of designated investment and operating costs of reservoirs made in selected technologies

Storage type	Energy storage cost [PLN / kWh]	Investment cost [PLN / kWh]
VRLA	2,78	1391
LiFePO4	4,03	8057
LTO	0,22	5069
EDLC	0,17	171428
LIC	0,15	152000

Source: own study

Boundary conditions, decision variables and objective function used in the model

In the model of energy development in the West Pomeranian Region, the LTO energy storage technology was selected, meeting the criteria of five types of system services (Table 6) and characterised by a lower cost of energy storage (Table 7). According to the forecast included in the draft Energy Policy of Poland until 2050, electricity production in the West Pomeranian Region will increase by approx. 30% in 2030, compared to 2015. Therefore, the energy production values for the year 2015 and the year 2030 are 10015,6 GWh and 11956,08 GWh, correspondingly (PEP2040 2019). The model in 2030 assumes that the potential of energy production from biomass in the West Pomeranian Voivodeship will be used in 27 per cent, in accordance with the provisions of the draft Polish Energy Policy until 2040. The power of energy produced from biomass will amount to at least 3228.14 GWh, while the installed capacity of wind energy in 2030 will increase to 1000 MW - according to the Program for the development of the energy sector in the Zachodniopomorskie Region by 2015, with a perspective by 2030. For the construction of optimisation models, the values of technical and economic parameters were first calculated, and the minimum or maximum levels of balance conditions (and not side conditions) were established. The model adopted 24 decision variables presented in Tab. 8.

Table 8. Decision variables used in the model

Variable	**Name**	**Unit**	**Remarks**
x1	generating non-renewable energy	kWh	
x2	generating energy from co-firing	kWh	
x3	generating water energy	kWh	from existing installations (until the end of 2017)
x4	hydropower generation	kWh	in new installations (from January 2018)
x5	solar energy generation	kWh	
x6	generating energy from windmills at domestic	kWh	
x7	generating energy from wind farms	kWh	from existing installations (until the end of 2017)
x8	wind energy	kWh	in new installations (from January 2018)
x9	generating energy from biogas	kWh	
x10	generating energy from biogas in high-efficiency cogeneration with a total installed electrical capacity of less than 1 MW	kWh	
x11	biogas energy generation	kWh	in new installations (from January 2018)
x12	generating energy from biofuels	kWh	
x13	generating energy from biomass combustion from existing boilers	kWh	until the end of 2017
x14	energy generation from biomass combustion from new boiler installations	kWh	from January 2018
x15	power generation from geothermal energy		
x16	total annual electricity production from various energy sources	kWh	
x17	the size of the cultivation of raw materials for biomass combustion - miscatus	kWh	
x18	the size of the cultivation of raw materials for biomass combustion - poplar	kWh	
x19	the size of the cultivation of raw materials for biomass combustion - mallow	kWh	

x20	the size of the cultivation of raw materials for biomass combustion - Jerusalem artichoke	kWh	
x21	the size of the cultivation of raw materials for biofuel combustion - rapeseed	kWh	
x22	the size of the cultivation of raw materials for biofuel combustion - cereals	kWh	
x23	the size of the cultivation of raw materials for biogas combustion - maise	kWh	
x24	the size of the cultivation of raw materials for biogas combustion - beets	kWh	

Source: own study

The objective function (minimised) consisted of four components:

1) production costs,
2) costs related to certificates,
3) costs of purchasing EUA allowances
4) energy storage costs.

In the optimisation model, only one function (L (x)) was minimised, which was a component of the above components. At the same time, cost coefficients were determined for each type of energy (from x1 to x15), which are included in the tab. 9, while the objective function parameters (from x17 to x24) include the costs of generating energy from energy crops and are included in the tab. 10.

Table 9. Cost factors for each type of energy [PLN / kWh]

Energy types	**Production costs**	**Certificate cost**	**Ecological costs (EUA)**	**Storage costs (LTO)**	**Total costs**
x1	0,72	0,00	0,0316	0,00	0,75
x2	0,93	0,00	0,0252	0,00	0,90
x3	0,20	0,12	0,0006	0,22	0,29
x4	0,20	0,12	0,0006	0,22	0,29
x5	0,40	0,12	0,0007	0,22	0,49
x6	0,24	0,12	0,0006	0,22	0,33
x7	0,24	0,12	0,0006	0,22	0,33
x8	0,24	0,20	0,0006	0,22	0,25
x9	0,70	0,12	0,0116	0,22	0,78
x10	0,70	0,12	0,0116	0,22	0,78
x11	0,70	0,20	0,0120	0,22	0,78
x12	1,10	0,12	0,0120	0,22	1,18
x13	0,28	0,12	0,0004	0,22	0,37
x14	0,28	0,20	0,0004	0,22	0,29
x15	0,28	0,12	0,0010	0,22	0,37

Source: own study

Table 10. Loss of soil fertility caused by the production of energy resources (in t/ha)

Energy resources	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}
Loss of soil fertility	0,18	0,35	0,17	0,07	0,04	0,5	0,34	0,5

Source: own study

The objective function of the decision model is as follows:

$$L(x) = 0{,}75x1 + 0{,}90x2 + 0{,}29x3 + 0{,}29x4 + 0{,}49x5 + 0{,}33x6 + 0{,}33x7 + 0{,}25x8 + 0{,}78x9 + 0{,}78x10 + 0{,}78x11 + 1{,}18x12 + 0{,}37x13 + 0{,}29x14 + 0{,}37x15 + 0{,}18x17 + 0{,}35x18 + 0{,}17x19 + 0{,}07x20 + 0{,}04x21 + 0{,}5x22 + 0{,}\ 34x23 + 0{,}5x24 \rightarrow \min$$

The boundary conditions assume that all variables must be non-negative and are as follows:

This condition implies the production of energy from non-renewable and renewable sources, which constitute the total energy production.

$$x1 + x2 + x3 + x4 + x5 + x6 + x+7 + x8 + x9 + x10 + x11 + x12 + x13 + x14 + x15 = x16$$

This condition assumes that the production of energy in the studied area will be equal to or greater than 11 956 080 000 kWh; it results from the assumptions of the Polish Energy Policy Draft until 2040. The project assumes that the surplus of energy generated in a given area can be exported to other regions.

$$x16 \geq 11\,956\,080\,000 \text{ kWh}$$

This condition assumes that within the framework of the European Commission, the CO2 emission target in 1990-2030 will be 30 per cent.

$$x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10 + x11 + x12 + x13 + x14 + x15 = 0.30\ x16$$

This condition assumes that the production of wind energy will be equal to or greater than 3 011 6 400 000 kWh in accordance with the assumptions of the Polish Energy Policy until 2040.

$$x6 + x7 + x8 \geq 3\ 011\ 640\ 000 \text{ kWh}$$

This condition, following the amendment to the Act on Investments in Wind Farms, commonly known as Anti-windmill, assumes that the total potential of the area is 84 000000 kWh

$$x8 \leq 84\ 000\ 000 \text{ kWh}$$

This condition assumes that following the assumptions of the Draft Energy Policy of Poland until 2040, the production of energy from biogas will be equal to or greater than 60 850 000 kWh

$$x9 + x10 + x11 \geq 60\ 850\ 000 \text{ kWh}$$

This condition assumes that, following the assumptions of the Draft Energy Policy of Poland until 2040, the production of energy from biomass will be equal to or greater than 322 814 000 kWh.

$$x13 + x14 \geq 322\ 814\ 000 \text{ kWh}$$

Generating energy from biogas combustion kWh

$$x9 + x10 + x11 = 30\ 450\ 000x23 + 10\ 960\ 000x24$$

Generating energy from burning biofuels kWh

$$x12 = 10\ 500x21 + 15\ 000x22$$

This condition assumes that the production of energy from geothermal energy will be equal to or greater than 0 kWh results from the assumptions of the Draft Energy Policy of Poland until 2040

$$x15 \geq 0 \text{ kWh}$$

Maximum production of conventional energy

$$x1 = 0 \text{ kWh}$$

This condition assumes that the production of energy from co-firing will be equal to or lower than 6 907 531 938 kWh, following the assumptions of the Draft Polish Energy Policy until 2040, November 23, 2018.

$$x2 \leq 6\ 907\ 531\ 938 \text{ kWh}$$

Production of new hydropower

$$x3 + x4 \geq 313\ 770\ 000 \text{ kWh}$$

Minimal solar energy production

$$x5 \geq 9\ 590\ 000 \text{ kWh}$$

Description of the model's construction is presented in details in study [50].

Discussion of results

Model optimisation with this objective function gives the following solutions:

Total energy production is 11,956.08 GWh (covers the demand of the studied area). The main energy production sources obtained by the optimisation model are:

- 4,200.07 GWh is the total energy production from co-firing,
- 320.50 GWh is hydropower from hydropower plants set up by December 31, 2017,
- 4.5 GWh is hydropower that can be produced in new installations from January 1, 2018,
- 187.99 GWh is the sum of solar energy from installations until December 31, 2018 (9.59 GWh) and new installations that will be built from January 1, 2018 (295.61 GWh),
- 3,575.08 GWh is wind energy generated in existing wind farms until December 31, 2017,
- 245.50 GWh is the energy that can be produced in new wind farms built from January 1, 2018,
- 30.45 GWh is energy produced from existing agricultural biogas plants until December 31, 2017,
- 12.96 GWh is the energy that can be produced in biogas plants with high-efficiency cogeneration with a total installed electrical capacity of less than 1 MW; from 1 January 2018,
- 54.06 GWh is the energy that can be produced in new biogas plants from sewage treatment plants and biogas from landfills, established on January 1, 2018,
- 30.00 GWh generation of energy from biogas in new installations from January 1, 2018
- 238.20 GWh is the energy generated in the existing biomass boilers until December 31, 2017,
- 3,049.94 GWh is the energy that can be produced in new biomass boilers from January 1, 2018,
- 6.83 GWh is the energy that can be generated in new geothermal installations from January 1, 2018,

The average cost of building 1 MW of energy would be PLN 9,315,120 or 2,076479 EUR if all-natural conditions and the emergence of new types of loads on the electricity market linked to the penetration of renewable energy sources.

The proprietary multi-criteria model of regional energy sector development, which takes into account economic and environmental criteria, allows for the generation of various types of solutions that may be helpful in the development of future energy development strategies by regional governments (Rajnoha et al., 2019; Tolstolesovaet al., 2019; Raszkowski and Bartniczak, 2018).

The compromise solutions obtained using the lexographic method provide a lot of information for local authorities regarding implementing various renewable energy scenarios that are critical under transition to low carbon energy future, building a carbon-neutral society, and implementing 100% RES scenarios. Without the possibility of developing regional renewable energy scenarios by considering local conditions and energy storage requirements, it is impossible to achieve a low carbon energy transition in the country.

Therefore, the research in the West Pomeranian region, as well as the calculations of the proprietary model, confirm the correctness of building a regional system based on alternative energy sources, including energy storage technologies. The built mathematical model and its validation confirm that it can be a valuable tool for decision-makers in formulating sustainable energy policy for the region (Svazas et al., 2019; Tvaronavičienė et al., 2018; and Stavytskyy et al., 2018).

Unfortunately, the state's current energy policy is not conducive to the creation of autonomous regional energy systems based on renewables, where the decision is being made based on the size and structure of energy produced in the region and plans of energy companies and the Energy Regulatory Office. The developed model and case study allow to enhance regional energy planning, and sustainable energy policy development on a regional level based on local government priorities and overcome some important renewable energy barriers (Lu et al., 2019).

The research also showed that the regional energy policy of the West Pomeranian region takes into account the specificity of the region to a small extent, that the main supplier of energy in the West Pomeranian region is coal energy. The only positive example is the development of wind energy. Nevertheless, due to the growing share of energy from renewable sources in the West Pomeranian Region, as shown in the case study, it will be necessary to expand the transmission and distribution infrastructure, including the most competitive energy storage technologies.

At present, the condition of the energy transmission networks in Poland cannot be described as satisfactory. The most important condition for the modernisation of the network should be the life cycle of the infrastructure. Most of the transmission and distribution infrastructure is currently in very poor technical condition. Most of the transmission lines were built in the 1970s and 1980s. Therefore, the average age of network assets for industry power is 40 years, so it is close to technical wear. In addition, the infrastructure dates back to a time when other technical standards existed. The lines were not designed for such a large energy transmission and for the implementation of energy storage technology.

It should also be remembered that each new generation source, including the use of energy storage, will require the construction of new connections, i.e. grid construction investments, which makes the situation in the transmission networks even worse.

In Poland, distributors are required to sign contracts with applicants for network connection, including the use of energy storage technology. This is due to Art. 7 sec. 1 of the Act of April 10, the Energy Law 1997 (Journal of Laws No. 89, item 625, as amended. 2006). In addition, the legislator obliged the transmission system operators to create instructions for the operation and operation of the electricity network (Article 9 of the Energy Law Act), which was aimed at proper planning of the use and development of power grids, taking into account the necessary related equipment and energy storage.

Therefore, it is necessary to implement an investment strategy for energy networks. The strategy should also take into account the issue of connecting distributed energy sources, including renewable energy sources, and the use of energy storage technologies. The conducted study provides the guidelines for decision-makers on such strategies development by providing optimal solutions for main energy generation sources development in the West-Pomeranian region from 2018 to 2030 and gives assessments of necessary energy storage.

Conclusions

The paper develops the model to address regional renewable energy planning issues and requirements of new infrastructure, including energy storage.

The future of the domestic energy industry depends on the condition of the energy transmission networks in Poland. To improve the situation, at least PLN 200 billion should be invested in the energy sector by 2030. This cannot be done immediately due to the high cost and length of the technological process. Other requirements are as follows:

- Searching for solutions to problems with sources of financing. Although the rate is structured in such a way that the recipient pays for the investment, the resources needed are so large that they would require commitment and raise prices to a level unacceptable to households and businesses. Due to the risk, the capital market is not able to provide such high financing at an acceptable price level. The solution could be to allocate part of the European funds related to renewable energy sources to construct connections and use energy storage technologies.
- Changes in the law. First, the so-called The act regulating the transmission corridor, determining the auxiliary nature of transmission and introducing a parametric payment system for property owners through which transmission corridors pass should be introduced. Besides, changes in the construction law and environmental conditions are necessary to improve planning processes. Today, it can take up to 12 years to obtain a building

permit and 25 or more years to build. Therefore, the average time needed to build a complex transmission network is 7-15 years.

Considering the long-term development and shaping of the country, and the advantages of renewable energy sources and energy storage technologies, we need to eliminate the main barriers to the development of this sector, including those related to transmission and distribution networks. However, it must be remembered that even if we manage to eliminate the barriers, we will have been waiting for results for the next 25 years.

The use of energy storage for the provision of energy supply services is becoming an increasingly important issue for the low carbon energy transition. This is possible thanks to developments in battery and supercapacitor technology over the past decades. This, in turn, was caused by the appearance of new types of loads on the electricity market, which are related to the development of electromobility and renewable energy sources.

Industrial research and experimental development lead to the development of technical solutions based on energy storage technology, providing innovative services that may be a response to the challenges faced by Distribution System Operators. Energy storage technologies are necessary for the energy balancing of selected areas and for improving and maintaining energy quality parameters.

The developed new optimisation model is also very useful for regional energy planning and supports the development of energy and climate plan for a municipality to achieve its targets for energy efficiency, renewable energy and greenhouse gas emissions reduction.

The role of renewable energy sources in the selected region will depend on the achievement of economic competitiveness by renewable energy sources in comparison with other energy generation technologies. However, it should be stated that the share of renewable energy sources in the energy balance will increase, also due to the implementation of the EU energy and climate policy covered by the EU New Green Deal, including low carbon energy transition paths.

The performed case study in West Pomeranian Region shows that due to the growing share of energy from renewable sources in the West Pomeranian Region, it will be necessary to expand the transmission and distribution infrastructure, including the use of the most competitive energy storage technologies. This will have an impact on the increase of costs of building additional MW of energy. However, future expansion of renewable energy sources will provide additional benefits for the municipality linked to economic growth and the creation of new jobs, including environmental benefits.

The conducted study has some limitations. The developed model does not consider weather conditions, dispatchability, modularity, and other important issues necessary to model development of intermitent renewable energy sources considering necessary energy storage technologies.

Future research is necessary to extend the developed model and to integrate some other important components linked to renewable energy technologies like dispatchability, modularity, weather conditions, and the impact of other policy incentives like subsidies, tax credits, feed-in prices etc.

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