

The role of pumped-storage hydropower plants as large-scale electrical energy storage in the power system

Rola elektrowni szczytowo-pompowych jako wielkoskalowych magazynów energii elektrycznej w systemie elektroenergetycznym

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Abstract:

The development of large-scale energy storage solutions is necessitated by the increasing integration of intermittent renewable energy sources into the Polish Power System to maintain system stability and flexibility. In this paper, the strategic role of pumped-storage hydropower plants (PSHPs) as critical electrical energy buffers is analyzed, with a focus placed on the specific case study of the Młoty PSHP project. The grid stability is significantly enhanced by the implementation of the Młoty PSHP. A comparative analysis against alternative storage technologies is also presented, through which the Młoty project's advantages as a large-capacity, long-duration storage asset are justified.

Keywords: electric power system, energy storage, power system stability, pumped-storage hydropower plants, renewable energy integration

Streszczenie:

Rozwój rozwiązań magazynowania energii na dużą skalę jest konieczny ze względu na rosnącą integrację odnawialnych źródeł energii o zmiennej charakterystyce pracy z Krajowym Systemem Elektroenergetycznym (KSE) w celu utrzymania stabilności i elastyczności systemu. W niniejszym artykule analizowana jest strategiczna rola elektrowni szczytowo-pompowych (PSHP) jako krytycznych buforów energii elektrycznej, ze szczególnym uwzględnieniem studium przypadku projektu PSHP Młoty. Wdrożenie PSHP Młoty znacząco poprawia stabilność sieci. Przedstawiono analizę porównawczą z alternatywnymi technologiami magazynowania, w której uzasadniono zalety projektu Młoty jako zasobu magazynowego o dużej pojemności i długim czasie działania.

Słowa kluczowe: system elektroenergetyczny, magazynowanie energii, stabilność systemu

1. Introduction

The dynamic development of renewable energy sources in Poland, which resulted in a record capacity increase of 6.6 GW in 2023, presents new challenges for the operational stability of the National Power System (KSE) [1]. The decarbonization process, assuming the decommissioning of stable coal-fired units with a total capacity of approximately 5–7 GW by 2030 [2], leads to a reduction in the physical inertia of the system and increases its susceptibility to rapid frequency changes [3, 4]. In this context, pumped-storage hydropower plants (PSHPs) play a crucial role as a proven technology for system-scale storage. They can shift energy surpluses in time and provide critical system services, such as frequency and voltage regulation [5–7]. The aim of

this article is to analyze the strategic role of PSHPs in the Polish power system, with a specific focus on the Młoty PSHP project [8]. The basic principles of operation for such installations are presented [9], and a review of existing domestic and global solutions is conducted [10–12]. Through the analysis of technical parameters and balancing capabilities, it is demonstrated that investment in large-scale energy storage is an essential element of a secure energy transition in Poland [4, 8].

2. Background and PSHP principles

A pumped-storage hydropower plant (PSHP) is a facility that combines the functions of electrical energy storage with energy generation, enabling long-term energy storage in the form of

potential energy of water in an upper reservoir [9]. The operation of a PSHP is based on a cycle of pumping and discharging energy, which occurs in two phases: the pumping phase and the generation phase (charging and discharging of the storage, respectively). During the pumping phase (charging process), water is pumped from the lower reservoir to the upper reservoir. This process requires the consumption of electricity from the grid and its conversion into potential energy of water. In the discharging phase (energy generation), water falls from the upper reservoir through water turbines, generating electricity that is supplied to the system when power demand is highest [9].

Table 1. Design parameters of Młoty PSHP [4]
Tabela 1. Parametry projektowe ESP Młoty [4]

Object	Parameter	Value
Upper Reservoir	Dimensions	~1241 m (length) x 417 m (width) x 22 m (depth)
	Total capacity	~6 mln m³
Lower Reservoir	Dimensions	~2.5 km (length) x 400–800 m (width)
	Total capacity	~13 mln m³
	Useful capacity	~6,3 mln m³
	Additional function	Flood protection (reserve: 7)
Lower reservoir dam	Dimensions	20 m (height) x 240 m (length) [4]

Table 2. Key technical parameters of the Młoty PSHP [4]
Tabela 2. Parametry techniczne ESP Młoty [4]

Parameter	Characteristics / Value
Installed capacity	Dependent on specific project scale
Storage capacity	From several hundred MWh to over 100 GWh (dependent on reservoirs and head)
Water head	200–1000 m
Cycle efficiency	Average 75–80%
Discharge time	4–9 hours (extendable with natural inflows)
Number of cycles	Virtually unlimited (> 20,000 cycles)
Reaction time	Approx. 2 minutes to reach full power from standstill
Technical lifespan	Even over 80 years [10]

Table 3. Hydrological characteristics of the Bystrzyca Łomnicka river [13]
Tabela 3. Charakterystyka hydrologiczna rzeki Bystrzyca Łomnicka [13]

Hydrological parameter	Value
Maximum flow	25,8 m³/s
Minimum flow	0,02 m³/s
Average flow	0,66 m³/s
Catchment area	~40 km²

3. Review of existing solutions

Poland possesses three implemented pumped-storage hydropower plants, which form the basis for system-scale electricity storage:

- Żarnowiec Power Plant – located in Puck County, Pomeranian Voivodeship, constructed between 1973–1983 with an installed capacity of 716 MW and a storage capacity of 3.6 GWh (capable of continuous operation at full power for 5.5 hours) [10, 14].
- Porąbka-Żar Power Plant – in Międzybrodzie Bialskie, Silesian Voivodeship, constructed in 1979 with a capacity of 540 MW, utilizing Lake Międzybrodzkie as a lower reservoir and an artificial upper reservoir atop Mount Żar [14].
- Żydowo Power Plant – in the village of Żydowo, Koszalin County. The Żydowo PSHP was the first of its kind in Poland and is the only one located between two natural lakes. Terrain topography and geology enabled the formation of two lakes approximately 1.5 km apart with a level difference of 82 meters [11].

PSHPs play a key role in contemporary power systems by providing both energy storage and comprehensive system services necessary for grid stability maintenance. In an era of dynamic growth in variable renewable energy (wind, PV), PSHPs represent a system-scale storage technology capable of shifting energy from low-demand periods to peak load periods. Furthermore, these plants provide critical system services such as frequency regulation (both primary and secondary), voltage control, and provision of reserve power capacities within minutes or seconds of activation [5, 6, 7, 15]. However, the development of new PSHPs faces numerous technical, geographical, and regulatory limitations. A fundamental constraint is the requirement for very specific topographical and geological conditions – the plant requires the existence or creation of two water reservoirs at significantly different elevations with an appropriate head, which limits potential locations to only a few percent of the land area. Additionally, new PSHP projects encounter significant regulatory and market obstacles – including complex environmental permit procedures and a lack of effective financial mechanisms in market structures to cover high capital expenditures [5, 7, 15].

4. Młoty Pumped-Storage Hydropower Plant – A Case Study

The Młoty PSHP project has over half a century of history – the first concepts were developed in the 1960s. The project's history is linked to many challenges, including changes in energy policy, environmental barriers, and social factors, which led to many years of investment stagnation [8]. Technical parameters place the Młoty PSHP among the leading European pumped-storage plants. The turbining capacity will reach 750 MW, while the pumping capacity will be 720 MW, with an energy capacity of 3.5 GWh and a planned technical head of 590 m [9]. The transition time from standstill to full generation is under 180 seconds, allowing for an immediate response to sudden drops in weather-dependent generation [9]. The round-trip efficiency (RTE), estimated at 77.3%, positions the project at the level

of European leaders [9]. Planned operational functions include: grid frequency regulation, reactive power compensation, and absorption of RES surpluses (especially in afternoon hours when PV generation peaks). Additionally, the plant has black start capability, enabling activation without power from the KSE [9].

Table 4. Comparison of selected PSHPs worldwide
Tabela 4. Porównanie wybranych ESP

Plant name and location	Power, MW	Capacity, MWh	Characteristics
Fengning, China	3 600	40 000	Largest in the world; key for stabilizing the Chinese grid [17, 16]
Ludington, USA	2 172	19 548	Commissioned in 1973; supports grid with nuclear plants [18]
Okutataragi, Japan	1 932	15 546	Important for balancing an island power system [12]
Dinorwig, UK	1 728	9 100	One of the fastest-reacting units in Europe [19]
Entracque, Italy	1 184	17 040	Alpine installation supporting regional grid stability [20]
Goldisthal, Germany	1 060	8 480	Represents German expertise in pumping technology [21]

5. Analysis of PSHP system balancing capability

The transformation of the National Power System (KSE) towards non-synchronous sources creates new, previously unseen challenges for grid stability [4, 22]. According to generating capacity of 750 MW and a pumping capacity of 720 MW, takes on key importance as an element supporting power system stability during the energy transition [4, 9]. Through the utilization of heavy rotating masses in hydro-generators, the facility provides natural mechanical inertia that photovoltaic and wind farms lack [4]. The plant can function as a synchronous compensator, allowing for precise reactive power regulation and voltage stabilization in transmission grid nodes in southern Poland [9, 23].

Selected technical and operational indicators of the Młoty project: Storage capacity: The project assumes an energy capacity of 3.5 GWh, which allows for approx. 4.7 hours of operation at full generating capacity [9]. Regulation dynamics: The transition time from standstill to full generation is under 180 seconds, enabling an immediate response to sudden drops in weather-dependent generation [4, 9]. Curtailment mitigation: Non-market RES generation limitations amounted to over 70 GWh in 2023 [1/S25]. Młoty PSHP enables the absorption of these surpluses during midday hours and their return to the system during the evening peak, which is essential for daily balancing [4, 24]. The Młoty project can provide physical stabilization of grid parameters by supplying mechanical inertia lacking in renewable sources. The technical parameters of the facility allow for rapid reaction to frequency fluctuations and effective management of RES energy surpluses. Consequently, this investment serves as a technical safeguard for the system PSE S.A. data, a record capacity increase in renewable energy sources of 6.6 GW (approx. 30% y/y) occur-

red in 2023, bringing the total installed RES capacity to 28.3 GW [1]. Simultaneously, Poland's decarbonization process assumes the decommissioning of stable 200 MW class coal- fired units, whose capacity in the system is expected to fall by approx. 5–7 GW by 2030, significantly lowering the system's physical inertia and affecting resource adequacy assessments [2, 3].

This phenomenon increases susceptibility to rapid frequency changes, measured by the Rate of Change of Frequency (RoCoF) index [4]:

RoCoF = df / dt (1)

The RoCoF index (1), which determines the rate of grid frequency changes (df) over time (dt), serves as a measure of power system stability; its limitation depends directly on the level of inertia provided by the rotating masses of generating units, preventing sudden parameter fluctuations and protecting the grid against cascading stability loss [4, 8]. In this context, the Młoty PSHP project, with a against the effects of coal-fired unit decommissioning, combining regulatory functions with large-scale energy storage.

Round-Trip Efficiency (RTE): The cycle efficiency index for this investment was calculated at 77.3% [23]. This index is calculated as the ratio of electricity supplied to the system during the turbin- ing phase to the total electricity taken from the grid during the process of pumping water to the upper reservoir, as expressed by the following relationship:

RTE = (Egenerated / Epumped) · 100% (2)

where:
RTE – round-trip efficiency expressed as a percentage, %
Egenerated – the amount of electricity generated by turbo-genera- tor sets and supplied to the grid in the generation phase, MWh
Epumped – the amount of electricity taken from the power sys- tem to fill the upper reservoir, MWh [9, 23].

6. Comparison with alternative technologies

An increase in the share of pumped-storage hydropower plants in the national energy mix is considered one of the key directions for improving the stability and flexibility of the National Power System (KSE) under conditions of a growing share of wind and photovoltaic generation [25]. The planned Młoty Pumped-Stora- ge Hydropower Plant is considered a large-scale energy storage facility with a power capacity of approximately 750 MW and an energy capacity of several GWh, capable of daily balancing of RES energy surpluses and rapid regulation of active power and frequ- ency [4]. Compared to other storage solutions, PSHPs enable sys- tem- scale energy accumulation with multi-decadal operational durability [25, 26].

Pumped-Storage Hydropower Plants (PSHP). Pumped-stor- age hydropower plants represent a mature technology for large- scale energy storage, in which energy is accumulated in the form of the potential energy of water. Very high power levels and high cycle efficiency in the range of 75–80% are achieved, while simultaneously maintaining very long operational durability and negligible capacity degradation, which predisposes them

for system operation [4, 26, 27].

Battery Energy Storage (Li-ion). Battery storage is characterized by high cycle efficiency and very good regulatory dynamics, which favors short- term applications. However, their utilization at a system scale is limited by relatively short operational durability and progressive capacity degradation over time, leading to an increase in unit energy storage costs [25, 28].

CAES (Compressed Air Energy Storage). The CAES technology is based on storing energy in the form of compressed air in underground geological structures. Power levels in the range of hundreds of MW are achieved; however, it is characterized by lower cycle efficiency and significant dependence on the availability of suitable geological conditions [28, 29].

Energy storage in the form of hydrogen (H₂). Hydrogen storage is based on the conversion of electrical energy into chemical form and its subsequent recovery. Although long-term energy storage is enabled by this technology, it is characterized by low overall conversion chain efficiency and durability determined by the lifespan of electrolyzers and fuel cells [30].

In the following table, selected energy storage technologies are compared regarding, among others, technical and economic parameters, including power scale, cycle efficiency, operational durability, and LCOES cost indicators, to assess their suitability for system operation with a high share of renewable sources [4, 26–30].

Table 5. Comparison of selected technologies [4]
Tabela 5. Porównanie wybranych technologii [4]

Criterion	PSHP	Battery (Li-ion)	CAES	Hydrogen
Power scale	hundreds of MW – GW	kW – hundreds of MW	hundreds of MW	MW–GW
Energy capacity	GWh	MWh – GWh	GWh	GWh – TWh
Storage time	hours – days	minutes – hours	hours – days	days – weeks
Cycle efficiency	75–80%	85–95%	45–70%	30–40%
Operational durability, year	50–100	8–15	>30	10–40
Capacity degradation	negligible	significant over time	negligible	negligible
CAPEX	high	moderate	high	very high
LCOE, €/MWh	100– 200	150–300	120–250	>300
Cost sensitivity	low	high	medium	very high
System utility	very high	local/regional	conditional	long-term

The advantage of the planned Młoty Pumped-Storage Hydropower Plant as a large-scale storage facility results from the combination of high power and energy capacity with high cycle efficiency and very long operational durability, which corresponds to the requirements of the National Power System under conditions of a growing share of wind and photovoltaic sources [4, 26, 27].

Pumped-storage hydropower plants enable energy storage in a daily horizon and the provision of system services, such as rapid power regulation, reserve maintenance, and frequency stabilization, which significantly increases system operational flexibility [4, 8, 31].

Compared to battery storage, the advantage of PSHP is represented by the lack of significant capacity degradation over time and a multi-decadal operation period, which translates into more favorable cost indicators over the entire life cycle at a large scale of stored energy [6, 25].

Relative to CAES technology, the alternative remains limited by strong dependence on geological conditions and typically lower cycle efficiency, whereas, compared to hydrogen storage, the fundamental advantage of PSHP is a significantly higher "energy-to-energy" conversion efficiency and better suitability for regulatory operation [29, 30].

Case analyses of Młoty PSHP further indicate that this project aligns with national system conditions and can perform the role of a key energy storage facility in the south-western part of the KSE [9].

7. Barriers and development perspectives of PSHP for młoty

The implementation of the investment in Młoty encounters a range of structural barriers that determine the project's schedule and risk.

Environmental and hydrological barriers. The greatest technical and legal challenge is the necessity to move approx. 6 million m³ of earth and deep interference in the Bystrzyca riverbed [4]. Location in an area of high environmental value necessitates obtaining a derogation from Article 4 (7) of the Water Framework Directive (WFD), which is a complicated process requiring proof of overriding public interest while demonstrating a lack of alternative solutions with less impact on water ecosystems [32, 33].

Economic and financial barriers. The estimated capital expenditure (CAPEX) at the level of 1,332.5 million EUR represents a significant barrier to entry [9]. Unlike battery technologies, which are characterized by lower initial costs, PSHP requires long-term financial support mechanisms. The main barrier is the lack of a stable capacity market model or contracts for difference that would account for the facility's 80-year lifecycle and ensure a return on investment under variable energy price conditions [9].

Social barriers. The long history of the project, dating back to the 1970s, led to a state of so-called "investment freeze" for the village of Młoty. The necessity for resident relocation and the change in the region's character from tourist-oriented to industrial generate a risk of social opposition, requiring the implementation of a transparent compensation policy and broad social consultations to avoid administrative blocks [4, 8].

8. Development perspectives and importance for transformation

Perspectives for the Młoty PSHP project stem directly from the assumptions of the "Energy Policy of Poland until 2040" and are crucial for the success of economic decarbonization [3]:

Synergy with nuclear power: Młoty PSHP will serve as an indispensable buffer for the planned first Polish nuclear power plant. The capability for energy absorption in the so-called night valley will allow the reactor to operate at constant, optimal thermal power, minimizing technical stress and increasing the economic efficiency of the entire nuclear system [4].

Offshore integration and grid development: In the face of offshore wind farm development in the north of the country, Młoty PSHP (located in the south) will enable the management of power surpluses transmitted via ultra-high voltage highways. Thanks to the planned 400 kV network expansion on the north-south axis, this facility will allow for wind energy storage during low-demand periods, reducing the necessity for offshore farm curtailment [34].

Sovereignty and system security: The facility in Młoty offers a unique capability for black start on a national scale. In the event of a system-wide blackout, the plant can provide voltage to the grid and initiate the system restoration process, making it a cornerstone of Poland's energy security as stable coal units are decommissioned [4, 22].

9. Conclusion

The conducted analysis confirms the hypothesis that the implementation of the 750 MW Młoty PSHP project constitutes a foundation for Poland's energy security during the transformation [4, 9]. As a facility equipped with heavy rotating masses, this power plant provides necessary mechanical inertia, directly improving system stability and protecting it from cascading parameter loss [4, 23].

Key conclusions drawn from the project analysis include:

Balancing and curtailment mitigation: Młoty PSHP will enable effective management of RES energy surpluses, reducing the phenomenon of curtailment, which exceeded 70 GWh in 2023 [1, 4, 24].

Technological synergy: The facility will serve as a necessary buffer for the planned first Polish nuclear power plant [4] and will enable the integration of energy from offshore wind farms [27].

System security: Thanks to its unique black start capability, the plant constitutes a critical resource in the process of potential system restoration after a blackout [4, 9, 22].

Despite significant barriers, including high capital expenditures (CAPEX) of 1,332.5 million EUR [9], complicated environmental procedures related to the Water Framework Directive [32, 33], and social challenges arising from the long-term "freeze" of Młoty village [4, 8], this investment is a strategically important resource. Results of the study clearly indicate that without large-scale energy storage with the characteristics of Młoty PSHP, a successful and safe energy transition in Poland will be difficult to achieve [8, 35].

10. References

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