technical transactions
No. 2024/003
environmental engineering
sciendo

The influence of the planned Solina-Jawor pumped storage power plant on the operating regime of the Solina-Myczkowce power plant

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Scientific Editor: Michał Zielina,
Cracow University of Technology
Technical Editor: Aleksandra Urzędowska,
Cracow University of Technology Press
Language Verification: Timothy Churcher,
Merlin Language Services
Typesetting: Anna Pawlik,
Cracow University of Technology Press

Received: February 26, 2024
Accepted: April 9, 2024

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing interests: The authors have declared that no competing interests exist.

Citation: Twaróg, B. (2024). The influence of the planned Solina-Jawor pumped storage power plant on the operating regime of the Solina-Myczkowce power plant. *Technical Transactions, e2024003*. https://doi.org/10.37705/TechTrans/e2024003

Abstract

The article presents an extended model of the Solina-Myczkowce pumped storage power plant with the designed new reservoir and Jawor power plant. Different design cases for the size of the reservoir located on Mt. Jawor were considered. In building the model, a modular approach was used to clearly distinguish elements of the model. In order to capture seasonal changes in both hydrological conditions and power demand values, a period of 365 days was assumed for the simulations. The simulations assumed the form of criteria defining on/off moments and defining the turbine/pump turbine operating regime using the daily variation of energy prices. All constraints arising from the physical parameters and limitations of the cascade facilities as well as those arising from the provisions of the current Water Management Manual for the Solina-Myczkowce cascade were taken into account. The model was designed and executed using the Matlab-Simulink interface. The developed model, assuming various solutions of the additional Jawor-Solina pumped storage power plant, allows multivariate analysis of the effects, both in the sphere of electricity production and financial . The flexible design of the model is a proposal with the help of which it is possible to develop and test decision-making mechanisms in the energy and financial area of cascade operation. Expansion of the energy cascade with a new element of the pumped storage power plant affects the functioning in its current form of the Solina-Myczkowce PSPS. The results show the directions of changes that should be made in the operating strategy of such an expanded energy complex. The analyses are supported by a number of charts and a commentary.

Keywords: Solina-Jawor PSPS, Solina-Myczkowce PSPS, optimisation, control criteria, Multi--Purpose Water Infrastructure

1. Introduction

The term multi-purpose water infrastructure of the water-economic system (MPWI – multi-purpose water infrastructure) (Naughton, 2017) fully captures how tasks are performed and objectives are achieved. Systems that are used for more than one purpose in economic, social and environmental activities increase the economic efficiency of large hydro projects and strengthen their position in the process of managing water and environmental resources (Kaczmarek, 2000; Twaróg, 2008).

The Solina-Myczkowce hydrotechnical facilities have been multipurpose hydrotechnical facilities since the beginning of their operation, performing the functions of electricity production, water supply, alimentation, retention, protection of the valley below against flooding, and recreation and tourism (Twaróg, 2009; Politechnika Rzeszowska, 2001; Dziewański, 2002; Słota, 2000; Kaczmarek, 1960). The production of electricity, is executed by the Solina power station, which performs the tasks of a pumped-storage power plant, and two Myczkowce power stations: a small pumped-storage power station and a larger derivation power station. This article considers the expansion of the existing Solina-Myczkowce power plant with an additional hydropower facility: the Solina-Jawor pumped-storage power plant.

2. Description of the current state of the facility

2.1. The catchment area of the Solina-Myczkowce reservoirs

The catchment area of the San River for the Solina cross section (Fig. 1) is 1,174.5 km^2. The catchment area for the Myczkowce cross section is 1,248.0 km^2. The Solina Reservoir is fed from two main tributaries – the San River and its right tributary the Solinka River. The average SSQ flow in the Solina cross section from the period of operation 1969–2006 was 22.7 m^3/s (Politechnika Rzeszowska, 2001; Dziewański, 2002).

Fig. 1. View of the Solina dam and reservoir (photo by Bąk, Krzeszowiak, Borowiec, Kordaszewski, Kozłowski)

2.2. Water management of the cascade

Currently, the Solina-Myczkowce cascade performs the following tasks:

- energy use of the retained water;
- protection against flooding on the San River;
- equalisation of perennial minimum flows of the San River below the Myczkowce cross section;
- supply of water for municipal, industrial and recreational purposes.

During normal operation, the priority is the implementation of tasks related to the fulfilment of tasks for the NPS, while during the flood period, due to the threat to the public in the valley below and the danger to the cascade facilities (the maximum capacity of the Myczkowce stage is less than the maximum capacity of the Solina stage), the priority is switched to protection against flooding. Implementation of the tasks of flood protection and maintenance of energy potential are conflicting tasks, which leads to the implementation of conflicting activities. In order to protect against flooding, it is required to lower the accumulation on the reservoir in order to prepare the so-called flood reserve.. Achieving energy goals requires maintaining the damming to as high a level as possible. All tasks performed must comply with the Cascade Water Management Manual. For the safety of the facility and the population living in the San River valley below, the only rational solution is to adopt priorities in the way water is managed on the cascade (Twaróg, 1995; 2008; 2009; 2023a; 2023b; Politechnika Rzeszowska, 2001; Dziewański, 2002; Słota, 1983; 2000; Kaczmarek, 1960; Malinowski, 1995).

2.3. Solina hydroelectric power plant

The Solina EW (Fig. 2) is a special type of hydropower plant with the ability to pump water from the lower reservoir to the upper reservoir. The basic data of the power plant is shown in Table 1.

The Solina Reservoir was established in 1968. At maximum damming, it accumulates 503.97 hm^3 of water, the usable capacity of which is about 300.00 hm^3, Table 1. The normal damming level is 420.00 m above sea level. The Solina Reservoir is a reservoir with a perennial equalisation of outflows (Politechnika Rzeszowska, 2001; Dziewański, 2002).

Fig. 2. View of the Solina-Myczkowce Hydroelectric Power Plant Complex Branch, PGE Energia Odnawialna S.A. (photo by Bąk, Krzeszowiak, Borowiec, Kordaszewski, Kozłowski)

Solina turbine generators supply active power to the power system during periods of peak power demand (morning, evening). In addition to active power, they also generate reactive power, contributing to frequency regulation in the system.

Table 1. Basic technical parameters of the Solina reservoir

Stacking Levels		[m asl]
Highest Level of Emergency Overloading (Maximum Level of Damming)	maxPP	421.50
Normal Level of Damming	NPP	420.00
Minimum Level of Damming	minPP	401.50
Capacities		[hm^3]
Total Capacity with Overstorage	[m asl]	503.97
Usable Capacity	401.5–420.0	275.70
Permanent Flood Reserve	417.2–420.0	50.00
Forcing Flood Reserve	420.0–421.5	31.93
Dead Volume	401.5	196.34

Source: own compilation based on (Politechnika Rzeszowska, 2001)

Table 2. Parameters of the Solina power plant

Turbine Powers		[MW]
Installed Power		(2 × 68) + (2 × 32) = 200
Classic Hydro Units		
In Turbine Operation	$H_{śr} = 55$ m	2 × 68 = 136
Reversible Hydro Sets		
In Turbine Operation	$H_{śr} = 55$ m	2 × 32 = 64
In Pumped Operation	$H_{śr} = 55$ m	2 × 30 = 60
Maximum Pumping Power		69
Turbine Gullets		[m^3/s]
Gullet In Turbine Operation	$H = 55$ m	(2 × 138) + (2 × 66) = 408
Oesophagus in Pump Operation	$H = 55$ m	2 × 52,5 = 105
Characteristic Heads		
Max GROSS	$H_{brutto\ max} = 61$ m	(420.0 – 359.0 m asl)
Min GROSS	$H_{brutto\ min} = 39$ m	(401.5 – 362.5 m asl)
Pumping is performed only on slopes less than 55.3 m.		

Source: own compilation based on (Politechnika Rzeszowska, 2001)

2.4. Myczkowce hydroelectric power plant

The Myczkowce Derivative Power Plant (Table 2) is located in Zwierzyn, to which water is supplied by an adit from the Myczkowcki Reservoir. Myczkowcki Reservoir is the daily equalisation reservoir for the intervention-regulation operation of the Solina EW and, together with Solina Reservoir, forms a cascade of reservoirs with strongly interconnected water management. The Myczkowiecki Reservoir provides lower water for the Solina Power Plant. The highest level of usable damming is 362.50 [metres above sea level]. The total capacity with over-pumping is 10.7 [hm^3]. The usable capacity is 4.4 [hm^3]. Due to its small capacity, it only allows for daily equalisation of outflow from the Solina reservoir and the accumulation of water for pumping by reversible turbines (Słota, 2000).

The power plant is equipped with two vertical turbine sets with Kaplan-type turbines, directly coupled to synchronous generators (Politechnika Rzeszowska, 2001; Dziewański, 2002; Twaróg, 2023a; 2023b). The basic parameters of the power plant are shown in Table 3.

Table 3. Parameters of the Myczkowce power plant

Turbine Powers		[MW]
Installed Power		2 × 4.15= 8.3
Turbine Gullets		[m^3/s]
Esophagus Installed		2 × 22.5 = 45
Heads		[m]
Minimum Head		19.2 [m]
Nominal Head		21.7 [m]
Maximum Head		22.7 [m]
Characteristic Heads		
Max BRUTTO	(362.,5 – 337.9) [m asl] Q_{min} = 6.0 [m^3/s]	24.6 [m]
Min BRUTTO	(359.0 – 338.,7) [m asl] Q = 45.0 [m^3/s]	20.3 [m]

Source: own compilation based on (Politechnika Rzeszowska, 2001)

3. Energy management of the Solina reservoir

The Solina EW is a CDGU (centrally dispatched generating unit), peak-pumped power plant, operating on retained natural inflow to the Solina reservoir and also serving as an emergency power plant. In addition to scheduled production, the Solina-Myczkowce power plant provides system services for the needs of operators. At any order of the NDC (National Power Dispatch), the power plant is intervened (generator operation, pumping operation and compensator operation). The power plant operates in the generator regime and in the pumping regime. Reservoir energy management involves the optimal use of reservoir capacity for power generation.

4. Characteristics of the Jawor project facility

In this concept of the Solina-Jawor PSPS (Fig. 3 and 4), the configuration of four Francis reversible turbines is analysed. The installed capacity of the turbines is proposed for 4 × 125 MW generator operation and a 4 × 135 MW pumping

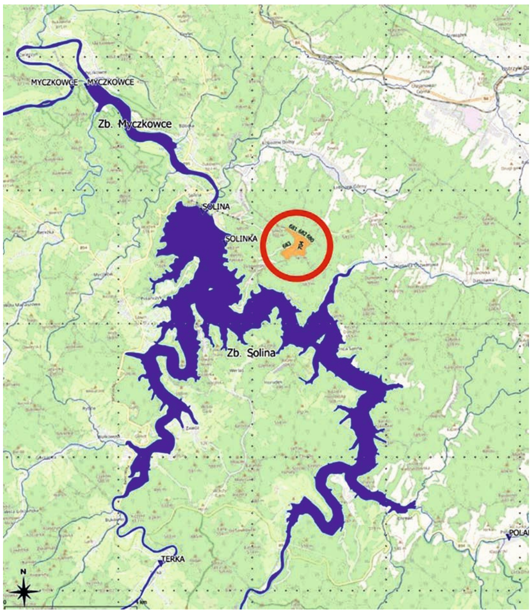

Fig. 3. The cascade of Solina-Myczkowce reservoirs and the location of the planned Jawor reservoir (own elaboration)

regime. The cycle efficiency of the power plant is about 75% (Politechnika Rzeszowska, 2001; Twaróg, 2009). The upper reservoir is an earthen, artificial reservoir with no natural inflow. It is located on the top of Mount Jawor (Fig. 4). The performed analysis assumed a reservoir capacity of 2 to 4 [hm^3] of water. The water table of the upper reservoir varies in the working range from 735.00 m above sea level to 755.00 m above sea level (Fig. 3–5).

Fig. 4. Topography of the summit of Mount Jawor (own elaboration)

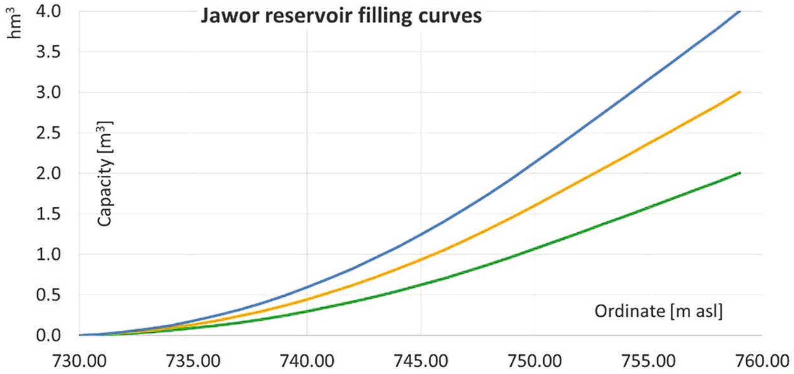

Fig. 5. Analysed variants of Jawor reservoir (own study)

5. Description of the simulation model of the operation of the Solina-Jawor power plant

The model was developed in the Matlab-Simulink interface (Fig. 6). Data relating to the historical inflows to the reservoir (Department of Geoengineering and Water Management) were adopted for simulation of the model. Power demand data were adopted for a period of the same length (Twaróg, 2023a; 2023b).

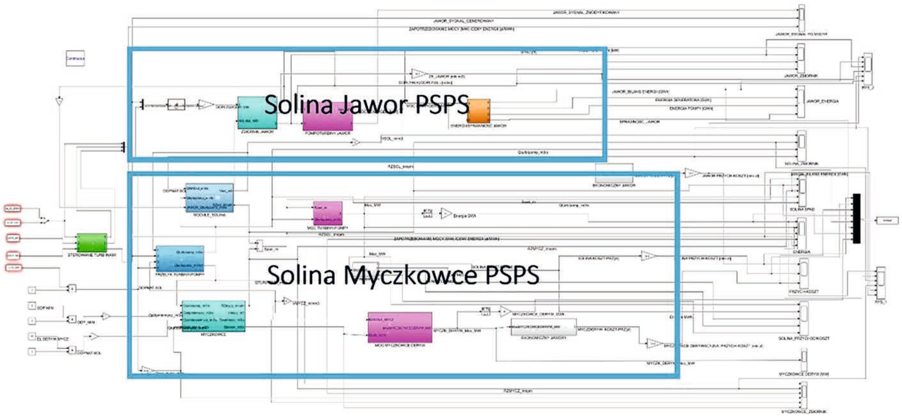

Fig. 6. Simulation model of the operation of the Solina-Myczkowce PSPS+ Solina-Jawor PSPS, Matlab- Simulink (own elaboration)

In creating the model, the focus was on the following elements:
Solina-Myczkowce PSPS model (Twaróg, 2023a):

- Input module – this block reads information about the power demand of the NPS, the size of the turbine/pump start-up criteria, and the size of the natural inflow to the reservoirs (these can be forecasts of these quantities).
- The module of building the control signal of generator and reverse turbines (Dziewański, 2002) – this is responsible for preparing the schedule of switching on and off of turbines and pump-turbines for both pump and generator operation.
- Control signal modification module (Dziewański, 2002) – this modifies the on/off control signal as a result of the limitation of the current retention capacity of the upper/lower reservoir (possibly due to the impulse of contingency operation, this may be a forecast).
- Turbine/pump module – this calculates the power and energy of turbines operating in the generator regime and reversible turbines in the generator and pump regime.
- Economic module – this performs revenue-cost calculations, taking into account current energy prices or their forecast.
- Output module – this presents the simulation results graphically or allows saving the results in formats such as ASCII.

Solina-Jawor PSPS model

- Jawor reservoir cooperation module with Solina reservoir – this is responsible for the water balance of the two reservoirs.
- Turbine/pump module – this calculates the power and energy of turbines operating in the generator regime and reversible turbines in the generator and pump regime.
- Economic module – this performs revenue-cost calculations, taking into account current energy prices or their forecast.

5.1. Turbine on/off signal building module and operating regime

The signal-building module is based on defined on/off criteria, which are set a priori by the system dispatcher (e.g. NDC – National Power Dispatch). They determine the on/off moments and the operating regime of turbines and pump-turbines. The on/off and regime change criterion can be built based on the power demand forecast or energy price forecast. In this simulation, the 24-hour distribution of regulated prices was used as the criterion. The lower criterion was set at 700 PLN/MWh while the upper criterion was set at 900 PLN/MWh (Fig. 7). This example solution can be modified through forecasts/interventions (Twaróg, 2023a; 2023b).

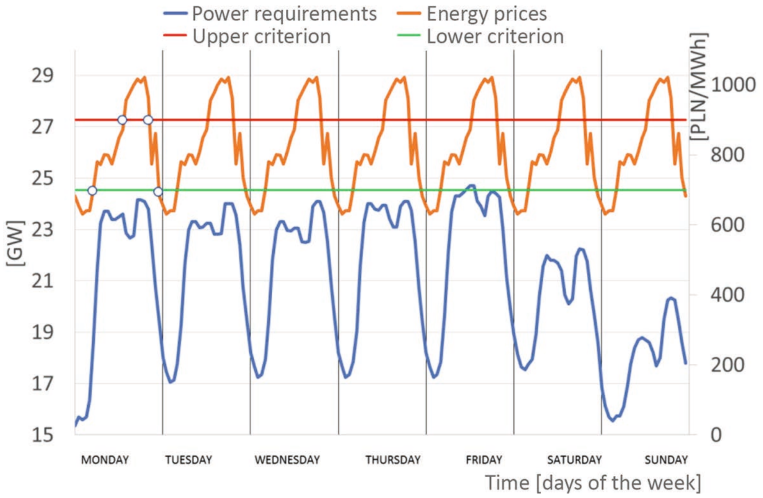

Fig. 7. Determination of switchover points from turbine to pumped storage operation and vice versa using a seven-day operating period as an example (own elaboration)

5.2. On/off signal modification module and operating regime

The actual parameters of the system and the constraints that are associated with the multi-purpose implementation of the cascade's objectives, not only in the energy dimension, but also in the area of water management, require modification of the turbine control signal. Constraints arise mainly from the permissible sizes of the capacities of the two cascade reservoirs, restrictions on the size of idle outflows, the ranges of turbine drops in the generator regime and reversible turbines for generator and pump operation. In addition, there is a need to take into account the so-called intervention, i.e. the change in the operating regime resulting from the needs of the NPS. The interpenetration of these constraints, scheduled operation and intervention, requires the reconstruction of the control signal (Twaróg, 2023a; 2023b).

5.3. Turbine/pump turbine operation

The turbine/pump turbine operation module calculates the power and energy of turbines operating in the generator regime and reversible turbines in the generator and pump regime. It takes into account the current filling of the Solina reservoir and the Myczkowce reservoir. The volumes of water in the reservoirs, reservoir fills, the resulting drop and the amount of energy consumed/produced are calculated taking into account the balance equations of the Solina-Myczkowce cascade (Twaróg, 2023a; 2023b).

5.4. Economic module

The economic (financial) module assesses the value of revenue from the sale of energy produced and the costs associated with buying the necessary energy for pumping.

The financial dimension is calculated according to the following approach:

$$P = \frac{1}{3600} \sum \int_0^T C_{REG}(t) \cdot N_{G_i}(t) dt$$

$$K = \frac{1}{3600} \sum \int_0^T C_{REG}(t) \cdot N_{P_i}(t) dt$$

$$Z = P - K$$

where: $C_{REG}(t)$ – regulated price [PLN/MWh]; $N_G(t)$ – turbine power in the generator regime [MW]; $N_P(t)$ – turbine power in pumped storage regime [MW]; P, K, Z – revenue, cost, profit [PLN].

6. Simulation results

Different design cases for the size of the reservoir located on Mt. Jawor were considered. Three variants of capacity were adopted: 2, 3 and 4 [hm^3]. The variants assumed constant filling ordinates. This means that only the horizontal dimensions of the analyzed reservoirs change in each variant. Calculations were performed for all 3 variants assuming a constant turbine control strategy. The on/off moments and the nature of the operating regime were determined based on the price change criteria. The size of the turbine overshoot of the Solina power plant was selected according to the following algorithm:

- turbine overshoot in the generator regime, assuming the capacity of the Solina reservoir:

$$\alpha > 0$$

$$Q_{TG} = \begin{cases} V_{\min} < V < V_{\max}\,;\ \min\left(Q_{TG}^{\text{nom}}, \alpha \cdot Q_{\text{dop}}^{NAT}\right) \\ V = V_{\max}\,;\ \min\left(Q_{TG}^{\text{nom}}, \alpha \cdot Q_{\text{dop}}^{NAT}\right) \\ V = V_{\min}\,;\ 0 \end{cases}$$

- gullet of turbines in the pumping regime:

$$Q_{TP} = \begin{cases} V_{\min} < V < V_{\max}\,;\ Q_{TP}^{\text{nom}} \\ V = V_{\max}\,;\ 0 \\ V = V_{\min}\,;\ Q_{TP}^{\text{nom}} \end{cases}$$

where: Q_{TG} – turbine gullet in the generator regime; Q_{TP} – turbine gullet in the pumping regime; Q_{TG}^{nom} – nominal gullet of the turbine in the generator regime; Q_{TP}^{nom} – nominal gullet of the turbine in the pumping regime; α – proportionality factor.

The rule defined in this way allows setting the operation of the turbines in the generator regime in proportion to the inflow to the reservoir, while the operation in the pump regime corresponds to the nominal values of the gullets for this regime. In the rule, the values depend on the capacity of the Solina reservoir, but the algorithm takes into account the limitations of both the Solina and the Myczkowce reservoirs.

In order to capture seasonal changes in both hydrological conditions and power demand values, a 365-day period was assumed for the simulations. The simulations assumed a form of criteria defining on/off moments and defining the turbine/pump turbine operating regime using the daily variability of energy prices.

6.1. Status Quo

The results for a 365-day simulation period are presented. The enlarged areas for selected time intervals are shown for the sake of readability of the graphs. The results of the calculations make it possible to see the relationships between the behaviour of individual objects/modules. Figure 8 shows the value of natural inflow, the periodic function of regulated energy prices, the ordinate of the Myczkowce reservoir, the ordinate of the Solina reservoir, the power of turbines/pump turbines and the energy balance cumulatively.

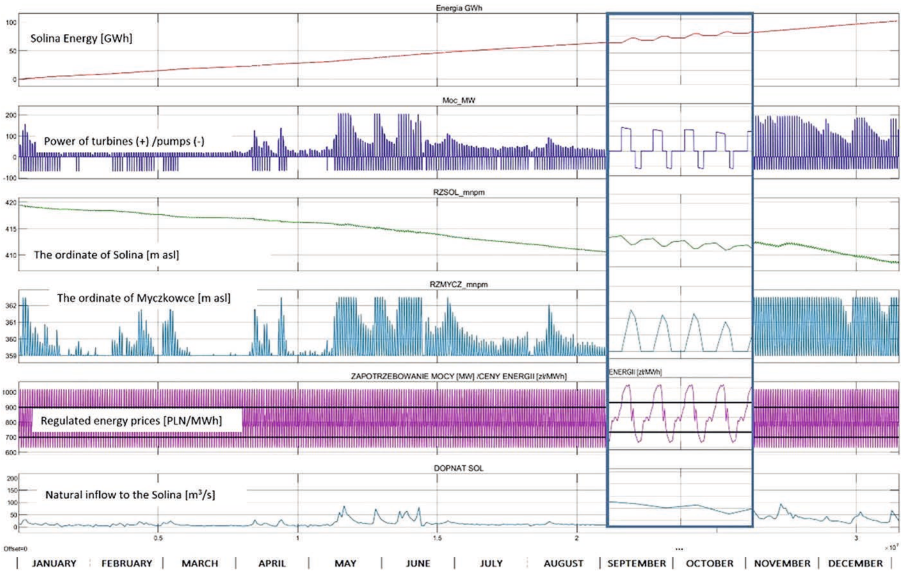

Fig. 8. Operation of Solina-Myczkowce PSPS (own elaboration)

6.2. Solina-Myczkowce PSPS + Solina-Jawor PSPS

Analysis of the operation of the Solina-Myczkowce PSP system and the system including the Jawor reservoir shows that one can notice an impact on the change in the operation regime of the current cascade, depending on the parameters of the Solina-Jawor PSPS and the capacity of the reservoir and the power of the turbines, only at high values of the parameters in comparison with those of the Solina PSPS (Fig. 9).

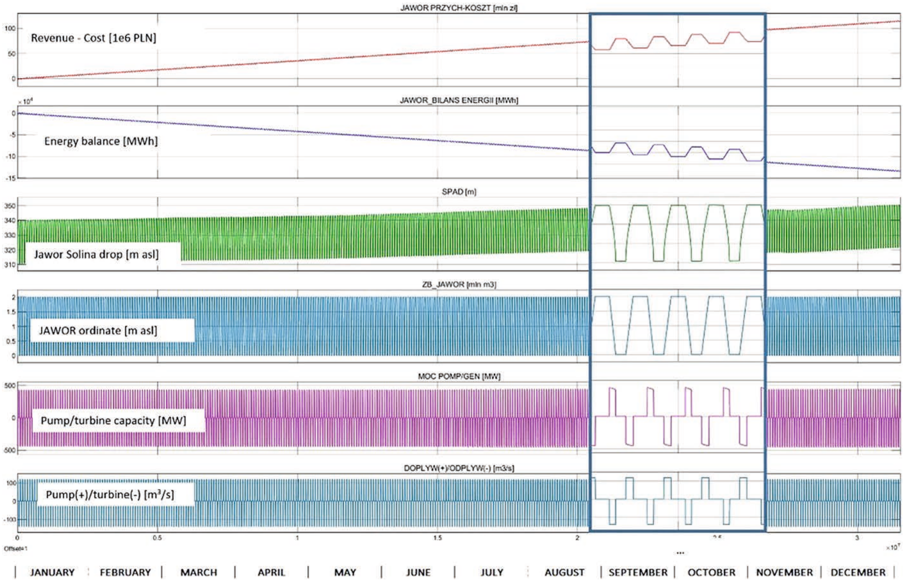

Fig. 9. Simulation results of Solina-Jawor PSPS (own elaboration)

The results of the simulation in financial and energy aspects are shown in Tables 4–6. The Jawor reservoir on average accumulates 1.77 [GWh] of energy. With the assumed turbine control parameters, the energy balance for 1 year of operation of the Solina-Jawor PSPS is (–135.5 GWh) to (–239.4 GWh). The efficiency of the system is at about 75%. The result of the financial balance is positive, at +34.96 [PLN 1e6] to +136.59 [PLN 1e6]. The results depend on the value of inflows to Solina-Myczkowce PSPS, the parameters and the control strategy. The positive financial result was obtained with the appropriate selection of turbine switching parameters, previously described in the construction of the turbine switching signal.

Table 4. The amount of stored potential energy by the Jawor reservoir

Capacity	Average lift height	Potential energy	
[hm³]	[m]	[J]	[GWh]
2	325	6.38E+12	1.77
3		9.56E+12	2.66
4		1.28E+13	3.54

Source: own elaboration

Table 5. Results of the annual energy and financial balance sheet

SOLINA-JAWOR		BALANCE SHEET [1e6 PLN]			BALANCE SHEET [GWh]		
[hm³]	alfa	JAWOR	SOLINA	MYCZKOWCE	JAWOR	SOLINA	MYCZKOWCE
2	10	34.960	119.184	38.978	–135.543	102.732	45.151
3	10	107.307	119.148	38.978	–201.426	102.687	45.151
4	10	136.590	118.920	38.978	–239.416	102.480	45.151
without Jawor reservoir	10	0.000	119.317	38.978	0.000	102.812	45.151

Source: own elaboration

Table 6. Statistics of the ordinate of Solina and Myczkowce reservoirs for one year

Solina-Myczkowce PSPS + Solina-Jawor PSPS					
Jawor reservoir	alfa	SOLINA		MYCZKOWCE	
		mean	std	mean	std
[hm^3]		[m asl]			
2	10	413.714	3.265	359.711	1.059
3	10	413.711	3.245	359.711	1.059
4	10	413.633	3.265	359.711	1.059
Solina-Myczkowce PSPS					
without Jawor Reservoir	10	413.833	3.240	359.711	1.059

Source: own elaboration

7. Elements of optimisation

Optimisation of the work of such an elaborate system can be performed either in a hierarchical system of task performance or for criteria that evaluate the work of the entire MPWI system. The basic criterion is safety (flood/water supply/energy) and financial effect. The multifaceted nature of the control problem of multi-tank energy systems and the concept of optimal control is difficult to define (Twaróg, 2009, 2023a, Malinowski, 1995, Słota, 1983). Decisions made on reservoirs affect the state of the entire water and power system (MPWI) (Naughton, 2017), so the criteria used should take into account the broadest possible multifaceted nature of the decisions made, measures of economic, ecological and social nature. In the broadest sense, the task of optimal control of the MPWI system is: multi-criteria, random, dynamic, multidimensional and non-linear (Twaróg, 2009, 2023a, Malinowski, 1995, Słota, 1983, Beibei, 2019, Padiyar, 2008).

8. Conclusion

The article presents simulation results of the developed model of Solina PSPS and Jawor PSPS. The model was designed and executed in the Matlab-Simulink interface. A modular approach was used to clearly distinguish specific elements of the model. Simulations of the model's operation were conducted for a period of 365 days. All constraints arising from the physical parameters and limitations of the cascade objects as well as those arising from the provisions of the current Water Management Manual for the Solina-Myczkowce cascade were taken into account. The model is a flexible proposal, with the help of which it is possible to develop and test decision-making mechanisms in the energy area of cascade operation with additional elements of expansion of the new designed facility.

Analysis of the simulation results shows that with such small parameters of the Jawor facility, the impact on the operating regime of Solina-Myczkowce is practically imperceptible. The volume of the Jawor reservoir is 0.73% to 1.45% of the part of Solina's working volume.

The following measures should be included in the recommendations for the analysis of such an extensive system:

- optimisation of charging and discharging cycles to maximise energy utilisation;
- adjusting the control to the weather forecast, energy demand, and the price of energy in the market;
- ensuring system stability in the context of frequent load changes;
- adapting the control strategy in environmental terms, e.g. by minimising water level fluctuations, limiting the volume of water discharged from the cascade, protecting wildlife;

- integration with energy storage, monitoring systems or artificial intelligence algorithms,
- operational security, stability and reliability of the PSP system.

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