Economic Feasibility of Converting Hydropower Plants to Pumped Storage: A Market-Based Approach with Renewable Energy Integration

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***Abstract*— Large-scale renewable energy sources, combined with advanced energy storage solutions, are critical for achieving a low-emission and climate-neutral power supply future. This paper evaluates the cost-effectiveness of repurposing an existing hydropower plant into a pumped-storage facility. The designated strategy is particularly promising for power systems with hydroelectric plants and plans for rapid expansion of solar and wind power stations, especially in scenarios where significant electricity price volatility is anticipated. The developed power system simulation model integrates sub-models for various energy sources and incorporates the interconnections of the Baltic States with Sweden, Finland, and Poland, adhering to Nord Pool electricity market rules. The optimization methodology involves steps such as renewable energy capacity planning and electricity price forecasting. The proposed framework shows significant promise for energy systems focusing on the rapid expansion of solar and wind power, particularly in contexts where substantial electricity price volatility is anticipated. The conclusions underscore the economic viability of the project and aim to guide high-level energy transition planners and decision-makers. The assessment is based on real-world data and utilizes custom software developed in Matlab.**

Keywords— climate change mitigation, energy storage, electricity marke, hydropower plant modification.

I. INTRODUCTION

The global ambition to reduce CO2 emissions has driven widespread adoption of renewable energy sources. However, integrating these sources into power systems presents significant challenges.

The primary issue with the global use of solar and wind energy is their variable and volatile electricity generation. In particular, the widespread adoption of solar and wind power demands greater efforts to balance highly variable energy generation with consumption. Therefore, the development of advanced energy storage solutions is critical to addressing these challenges and ensuring a reliable energy supply. In this context, economic performance indicators, such as costs and profitability, are crucial factors in determining the choice of storage technologies. One of the most attractive groups of storage technologies is based on hydropower units [1]-[5]. Hydropower plants are widely used and currently account for the largest share of renewable energy production worldwide [3]-[5]. In 2018, global installed hydropower capacity reached 1,292 GW, generating 4,200 TWh of electricity. Countries with a significant share of hydropower in their energy mix have a distinct advantage as variable renewables gain prominence. This advantage lies in hydropower's ability to provide substantial flexibility and storage capacity for electricity systems (SES) [6]. Most existing hydropower plants (HPs) typically consist of two reservoirs, a configuration that can be optimized to enhance energy generation and consumption flexibility without building new dams [6]. This flexibility can be achieved by converting hydroelectric power plants into pumped hydro energy storage (PHES) systems. Such conversions involve installing pumps to transfer water to a higher reservoir during periods of low-cost energy availability. PHES are the most widely deployed storage systems in modern power grids. The world's total installed capacity of PHES is around 160 GW in 2021, with global storage capability around 8,500 GWh in 2020. PHES capacity is expected to grow from 161 GW in 2018 to 300 GW in 2030 and 325 GW by 2050 [6]. During low demand and excess power generation, PHES converts electricity into gravitational potential energy by pumping water from a lower reservoir to an upper reservoir for storage. In high demand or supply shortages time moments, PHES reverses the process and works as HP to generate electricity.

Numerous studies highlight the growing interest in developing pumped-hydro energy storage using existing hydro power plants, particularly in regions heavily dependent on solar and wind energy, with limited interconnection capacity [7]-[9]. While the literature extensively covers the modelling and optimization of PHES [10]-[12], most research focuses on short-term scheduling, typically within daily or hourly intervals. Few studies address long-term planning,

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which is crucial for strategic energy supply. Although some research explores PHES in various electricity markets [11], [12], these typically focus on short- to medium-term horizons. The integration of pumped hydro energy storage with large-scale renewable energy sources and conventional natural gas-firing power plants remains underexplored. These gas-fired plants are typically used to meet power demand during periods when renewables fall short. Optimizing such systems poses significant challenges, requiring long planning horizons (exceeding one year) while maintaining high temporal resolution (hourly or finer), which adds to the complexity of the optimization process [12].

To address these challenges, this paper presents an optimization model for interconnected power systems, employing modelling techniques as detailed in our previous studies [13]-[15].

The primary objective of this article is to assess the required investment and profitability of reconstructing an existing hydroelectric power plant, considering the planned growth of renewable energy sources (RES), the limited capacity of transmission lines, and the specific conditions of the Baltic Sea region's power systems and the Nord Pool electricity market.

To achieve this goal, several key activities were undertaken:

- Case Selection: The Plavinas hydropower plant (total capacity: 900 MW) was chosen as a case study for assessing the feasibility of reconstruction. The idea of modernizing the Plavinas plant has been under consideration for over two decades but was previously dismissed due to a lack of profitability. However, the rapid deployment of RES and increased electricity price volatility in recent years have significantly altered the economic and operational landscape, warranting a reassessment of earlier conclusions.
- Regional Forecasting: A forecast of significant growth in the regional generator portfolio was developed, highlighting the increasing share of renewable energy sources and rising market price volatility. This forecast is informed by observed trends, including the rapid growth of RES, which accounted for 30% of electricity production in 2023 [16]-[19]. This trend underscores the growing need for greater flexibility in managing energy sources. Additionally, since 2020, there has been a notable increase in hourly electricity price fluctuations throughout the day, further emphasizing the importance of adaptable energy systems
- Model Development: Alternative power system models were created, incorporating RES and energy storage units, with a focus on estimating the profitability of a proposed pumped hydro energy storage facility.
- Market Simulation: An electricity market framework was designed, and power system operations were simulated to evaluate system performance under various scenarios.

These activities were carried out using the methodologies and tools described in our previous studies [13]-[15].

The core contributions of this paper include demonstrating how the modernization of a hydroelectric power plant can enhance profitability while increasing the power system's capacity to integrate renewable energy sources. The research findings provide an estimation of the necessary investments and the projected profitability of the proposed new unit.

The rest of the article is organized as follows: Section II defines the peculiarities of power systems in the Baltic Sea region. Section III presents a brief description and formulation of the problem and the models used. As well Section III showcases the results, including estimates of required investments, plant capacities, zonal electricity market prices, and recommendations for decision-makers. Finally, Section IV is dedicated to the conclusions.

II. Overview of the Power System Under Study

The study focuses on the Baltic Power System (BPS) as its object of analysis. This integrated power system encompasses the energy networks of the three Baltic states: Latvia, Lithuania, and Estonia. Fig. 1 illustrates the geopolitical positioning of these Baltic countries (depicted with red-yellow borders) on the map of Northern Europe. The red lines indicate the boundaries of neighboring countries with energy systems connected to the BPS via transmission lines, facilitating electricity import and export operations.

The upper left section of the Fig. 1presents a simplified structural diagram of the Baltic Power System, highlighting its primary electricity generation types: PSHP (pumped-storage hydropower plants), CHPP (combined heat and power plants), HP (hydropower plants), SPP (solar power plants), and WPP (wind power plants). A significant role in ensuring reliable electricity supply is played by:

- Thermal power plants that use natural gas as fuel, with a total electricity generation capacity of approximately 1.5 GW.
- High-voltage transmission lines connecting to Poland, Finland, and Sweden, with a total capacity exceeding 2 GW.

In the simplified structural diagram of the BPS, the generation source proposed for modification—namely, the cascade of hydropower plants on the Daugava River—is highlighted with a blue box.

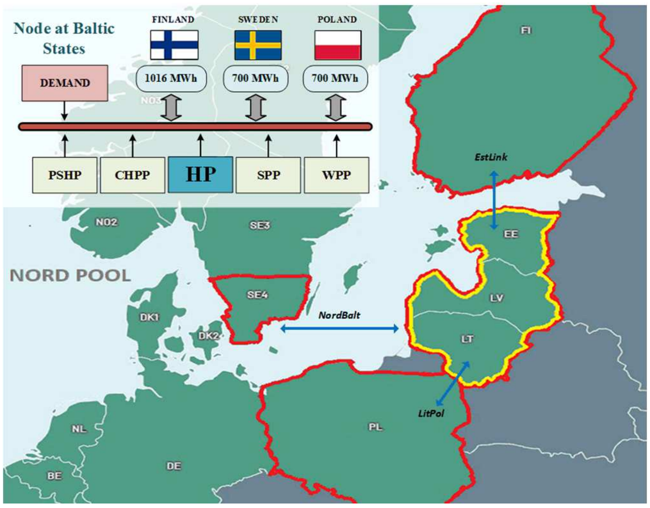

Fig. 1. The geopolitical allocation of power systems under investigation and the portfolio of the power plants and the interconnections.

A simplified diagram of the Latvian HPs cascade, as depicted in Fig. 2, provides an overview of the power generation system's structure, highlighting the interconnections between the plants and their collective role in energy generation.

A. General Review of Latvian HPs cascade

Depicted in Fig. 2, the Latvian hydropower plants cascade (total capacity 1.5 GW) is located along the Daugava River and includes three major hydroelectric plants: Plavinas HP, Kegums HP, and Riga HP [20]. This cascade plays a crucial role in Latvia's energy production – more than 40 % of the annual power demand is delivered. Moreover, in the BPS infrastructure cascade of Latvian HPs mitigate around 10% of annual power demand.

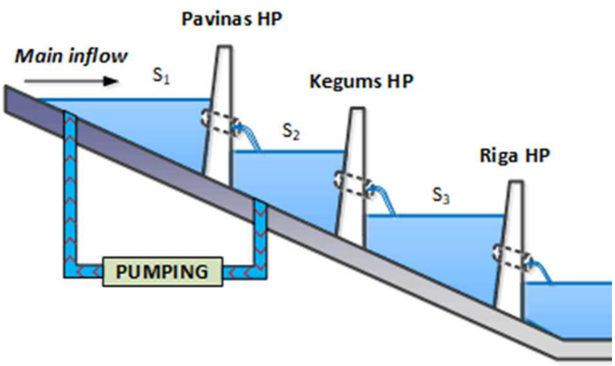

Fig. 2. Simplified diagram of Latvian HPs cascade

The Fig. 2 indicates that the planned modernization of the Plavinas Hydropower Plant involves the installation of pumps, thereby enabling the capability for water pumping. Let us note that the cascade under consideration comprises three reservoirs with relatively small storage capacity. The hydroelectric stations are classified as being close to "run-of-the-river" [21] systems, as they can only ensure charge mode for a few hours in advance.

The analysis of the Plavinas HP modernization impact on the BPS operation profitability involves creating scenarios and forecasts for time-series processes, predicting key variables such as electricity prices, energy demand, water inflow, photovoltaic panel and wind turbine generation volumes, and power flows due to power system interconnections. The developed mathematical model includes determining energy and corresponding prices for each hour and simulating market participant behavior. The estimated market clearing price (MCP) and accepted generator and load energy are also assessed.

As a result, the economic performance of the pump-storage unit is evaluated, considering hourly energy market costs and revenue for the power plant.

III. Modelling

A. The objective function and constraints

There is an assumption that the pumped hydro energy storage system generates revenue by time-shifting electrical energy: charging the upper reservoir during off-peak periods when prices are low and discharging during peak periods when prices are high. The primary objective of the hydropower plants cascade operation is to maximize profit. The objective function is defined in equation (1):

$$\sum_{i=1}^{T}(w_i^P + w_i^K + w_i^R - w_i^{PUMP}) \cdot C_i \rightarrow max \qquad (1)$$

where T is a planning period (8760 hours); i stands as a specific hour; w_i^P; w_i^K; w_i^R; w_i^{PUMP} generated or consumed(w_i^{PUMP}) electricity in the hour i by the Plavinas HP (MWh); Kegums HP (MWh) and Riga HP (MWh); C_i is an electricity market clearing price MCP at the hour i (€/MWh).

The optimization procedure runs over a full year, using an hourly discretization step. Consequently, the operation of the cascade spans 8760 hours. The procedure (1) must be executed while accounting for constraints expressed through equations or inequalities. The constraints reflect technical limitations, the laws of physics, and energy market regulations. These are typically represented by nonlinear equations containing random variables. As a result, the task becomes nonlinear, stochastic, and practically intractable [12]. Simplifying the problem is necessary and can be achieved through three main approaches: 1. Linearization of Objective Function and Constraints: this step involves simplifying the mathematical problem by approximating nonlinear components (e.g., objective function or constraints) with linear ones. 2. Assuming that the prices C_i for i=1…8760, can be described removing uncertainty.3. Neglecting the influence of PSHP mode on market prices, it means the analysis disregards how the operation of the PSHP might affect global market prices. In such case, the linearized problem remains controllable, even when involving tens of thousands of optimization variables.

B. Forecasting Energy Market Dynamics: Prices, Consumption, and Renewable Generation

Modelling hourly market clearing prices for an annual planning period is the central and most challenging task of the considered problem. In a competitive liberalized electricity market, a PHES operator must compete with other market participants while adhering to established rules. These rules are designed to align with the market-clearing principle, ensuring that electricity demand is met by selecting the most rational and equitable mix of generators. To achieve this, the PHES operator must offer energy bids within the constraints of the market framework. Usually bid of energy include energy volume and price for each hour of planning period. As a result of trading, the market price of energy is determined for each hour. If it exceeds the specific generator's offer price, the offer is accepted, and, according to Nord Pool rules [22], the market price is paid for the energy. Preparing such a proposal is a sophisticated task [12], as it involves short-term price forecasting and is typically addressed using optimization techniques. In this article, we address the complexities by adopting the following key assumptions: 1. When renewable energy sources generate more electricity than can be consumed (excluding storage units) or exported, the market price is set near zero. This assumption is based on the premise that renewable energy producers offer their electricity at a low price to ensure their proposals are accepted by the market operator. 2. When renewable energy sources, combined with imports, fail to meet the energy demand of consumers, the market price is high and corresponds to the cost of reserve plants**.** Gas-fired power plants [23] are utilized as reserve stations, activated only in cases of insufficient capacity from renewable energy sources. We assume the cost of energy generated by these plants to be €300 per MWh. This selected price ensures the preservation of the annual average electricity price observed in the Baltic power systems in 2024. 3. When energy consumption is met by a combination of renewables and imported power, the market clearing price is determined in accordance with Nord Pool's rules. This process considers the predicted prices of neighboring systems and selects the cheapest energy source to maintain energy balance [24]. Electricity prices and renewable generation depend on the volume of renewable energy sources to be installed in the future. To account for uncertainty, capacity projections are structured into scenarios expected in 2040. The key characteristics of the selected scenarios are summarized in Table I. The maximal value of total power consumption, total generation and rated capacity of each kind of power plant is depicted. We present only fully renewable generation: pumped-storage hydropower plant (PSHP), hydropower plant (HP), solar power plant (SPP), wind power plant (WPP), biomass power plant (BPP). These scenarios account for: a moderate increase in energy demand, the shut-down of all natural gas and coal-fired power plants, maintenance existing capacities of hydro and biomass power plants and the rapid building and deployment of solar and wind plants.

TABLE I. DEVELOPMENT SCENARIOS OF BPS 2040

	S_1	S_2	S_3	S_4	S_5
Demand, TWh/y			39.83		
HP, MWh/h			1 727		
SPP, MWh,h	1 600	2 200	2 800	3 400	4 000
WPP, MWh/h	5 000	7 000	9 000	11 000	12 000
PSHP, MWh/h			1 625		
BPP, MWh/h			522		
Pump, MW			90		
MCP €/MWh/y	77.01	70.89	67.66	65.46	64.92

According to the data presented in Table I, the cumulative annual demand of the BPS for the year 2040 remains consistent across all five scenarios. The installed capacities of hydropower plants, pumped-storage hydropower plants, and biomass power plants are assumed to remain unchanged compared to 2024. Table I specifies the rated capacity of the pumps in the planned modernization of the Plavinas Hydropower Plant (parameter Pump = 90 MW) [25]. The last row of Table I shows the dependence of the average annual electricity price on the modelling scenario.

The installed capacities of solar panels and wind farms vary depending on the scenario. Fig. 3 illustrates this relationship.

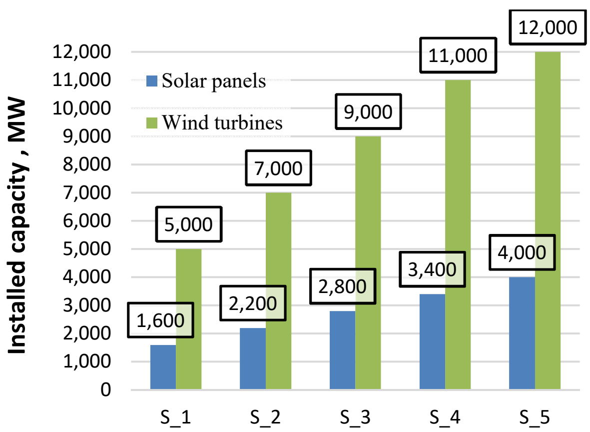

Fig. 3. Installed capacities of RES according to modelling scenarios

The monthly volume of electricity generated by RES is shown in Fig. 4. It can be observed that the highest RES generation occurs from April to July, coinciding with the longest days of sunlight in the Baltic region.

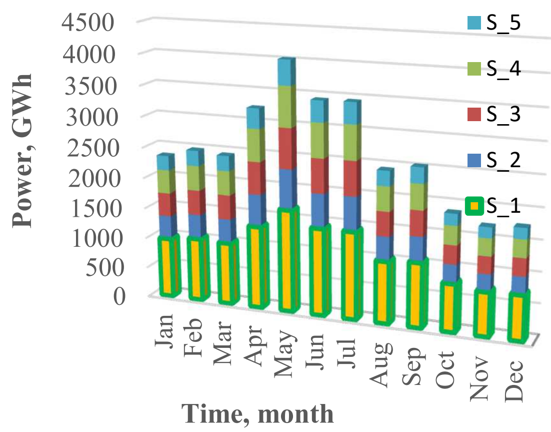

Fig. 4. Dependence of an average monthly power generation by RES on the modelled scenario

Fig. 5 depicts the relation mentioned in a more detail manner i.e. the monthly average forecasted electricity prices according to the modeled scenario.

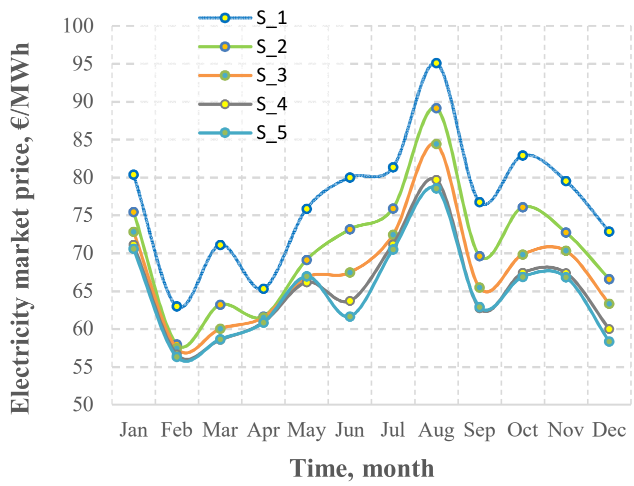

Fig. 5. Monthly average electricity prices in BPS 2040

C. Outcomes of the modeling

The profit generated by the cascade of Latvian hydropower plants before the modification of the Pļaviņas hydropower plant (green bars) in 2040 across all modelling scenarios is presented in Fig. 6. The analysis reveals that the maximum revenue for the hydropower plant cascade is achieved under Scenario *'S_1'*. This scenario, marked by a lower installed capacity of renewable energy sources, leads to higher average electricity prices, thereby increasing revenue from hydropower-generated electricity. However, it is important to note that the decision to construct additional renewable power plants and pumped storage plants is made by different investors. As a result, the implementation of scenarios '*S_2*' through *'S_5'* remains feasible, as they are managed by the owners of solar and wind plants. However, owners of hydropower plants must account for and adapt to potential profit reductions. Fortunately, the installation of pumps can help mitigate this impact by providing additional income opportunities.

Fig. 7 depicts additional electricity generation and the corresponding profit, both arising from the modernization of the Pļaviņas HP. An analysis of Fig. 7 reveals that the lowest values of extra electricity generation and corresponding profit for the Latvian hydropower cascade occur under scenario '*S_1*', characterized by least integration of RES.

In contrast, the highest values of additional electricity generation and extra profit are observed in the final scenario ('*S_5*'), which reflects the maximum installed capacity of RES.

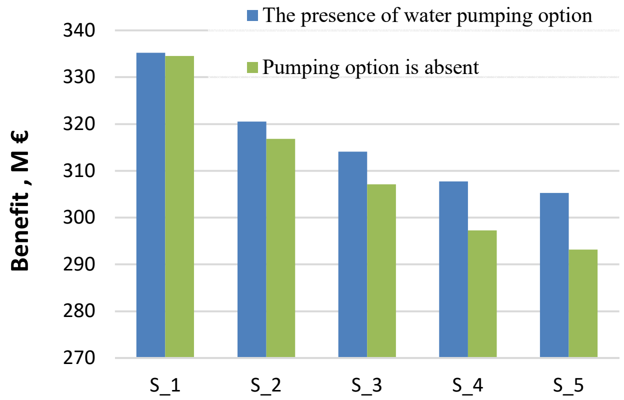

Fig. 6. Dependence of an annual profit of Daugava HPs cascade on the modelling scenario

In this case, the influence of the pump becomes evident, as it is activated when electricity prices drop to zero—that is, when the output of renewable energy exceeds consumption. Without the pump, the energy system achieves balance by curtailing a portion of solar or wind generation. The pump, however, enables the accumulation of this excess energy, allowing it to be converted into electricity at a later time.

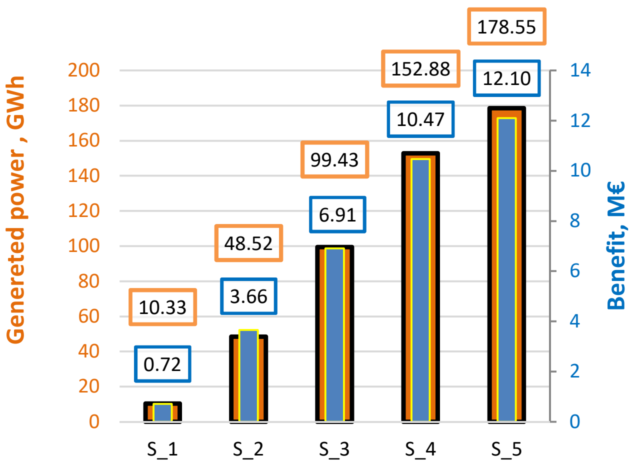

Fig. 7. Additional annual electricity generation (orange) and profit (blue) of Latvian HPs cascade as a result from the implementation of the pumping option

D. Economic evaluation

To estimate the profitability of the actions under consideration, the financial metric *Return on Assets (ROA)* will be applied [26], which measures a company's ability to generate profit from its asset:

$$\text{ROA} = \frac{(Income_{after} - Income_{before})}{OCC} \quad (2)$$

where

'$Income_{after}$' – annual profit of Latvian HPs cascade with pumping option, M€; $Income_{before}$ – annual profit of Latvian HPs cascade with pumping option absent, M€; '*OCC*' stands as overnight construction costs.

According to [25], the investment costs for the modernization of the Plavinas HP into a PSHP are 1200 €/kW. As previously mentioned, the potential total capacity of the water pumps is 90 MW. OCC stands as multiplication of the mentioned values:

$$OCC = 90\ MW \cdot 1200\ €/kW = 108\ M€ \quad (3)$$

Table II presents the Return on Assets calculations for the all scenarios. The results of ROA estimation for each analyzed scenario reveals a strong positive correlation between the installed capacity of renewable energy sources and the profitability of the Plavinas hydropower plant modernization. A comparison of scenarios '*S_1*' and '*S_5*' shows that the ROA increases by nearly 17 times.

TABLE II. RETURN ON ASSETS

Scenarios	ROA, %
S_1	0.66%
S_2	3.39%
S_3	6.40%
S_4	9.70%
S_5	11.21%

The estimated ROA values in the last scenario exceed 10%, which is generally considered strong performance. Such a value, as seen with companies like Rockwell Automation [27], should attract the attention of investors.

Taking into account that the mass ratio of CO_2 to CH_4 is 2.745, and given that 1 m^3 of methane weighs approximately 0.717 kg, we can estimate the mass of CO_2 produced from 1 m^3 of methane as 1.970 kg. This corresponds to approximately 0.320 kg of CO_2 per kWh of electricity generated in gas power plant. Consequently, the additional 178.55 GWh of electricity generated by the hydro power plant (see Fig. 7) offsets approximately 57 136 tons of CO_2 emissions.

IV. CONCLUSIONS

Efforts to mitigate climate change are driving the massive deployment of solar and wind generation, which in turn is increasing the variability of power prices. In such circumstances, energy storage solutions, particularly pumped storage power plants, play an increasingly critical role. Existing hydro generation units can be upgraded to create economically viable and beneficial conditions for the power generation mix within energy systems. This study confirms the feasibility of modernizing the Plavinas hydropower plant This upgrade, which introduces a pumping mode, not only enhances the hydro plant's operational efficiency but also boosts the annual electricity output from renewable sources. The return on assets, calculated based on an average annual electricity price of approximately 70 EUR/MWh, ranges from 0.66% to 11.21%, presenting a promising opportunity for investors.

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