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Original Research Article

Prefeasibility analysis of the Pumped Hydro Storage (PHS) system in Türkiye: A case study on a hybrid system

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ABSTRACT: Pumped Hydro Storage (PHS) power plants aim to exploit the price difference between storing and generating electricity. These power plants operate by pumping water from the lower reservoir to the upper reservoir, consuming energy, and generating electricity by transferring water from the upper reservoir to the lower reservoir. There is no pumped storage power plant in Turkey yet, and it is in the planning stage. This study aims to provide a preliminary feasibility analysis of this investment from an economic and technical point of view and to contribute to this issue through the recently announced feed-in tariff for PHS. The planned PHS at Gökçekaya Dam was considered a proposal in this study and was carried out using a developed algorithm. The algorithm determines the optimal installed capacity of hybrid energy. This feasibility analysis is based on two scenarios. The difference between the first and second scenarios is due to the investment cost of the PHS system. Additionally, the second scenario considers an integrated hybrid Solar Hydroelectric (SHE) system. Each scenario is evaluated in terms of base price, average price, maximum feed-in price, and market peak price. The result of the study is that only the market price represents a remarkable payback period for pumped storage power plants. As a result of the study, it was found that it's possible to support the pumped storage power plant with a hybrid solar power system and market price if only the storage volume is increased. The feed-in tariff should be set to cover the demand. In the first scenario, only the PHS was evaluated, and after completing the economic analysis, the investment has a payback period of 28.39 years for the market peak price. If the PHS facility is supported by a hybrid solar energy system for internal energy needs, the payback periods can be reduced. In the first scenario, the investment has a payback period of 18.05 years, supported by integrated hybrid solar energy. In the second scenario, the PHS investment has a payback period of 9.63 years for the highest price on the market. The investment has a payback period of 8.66 years, which is supported by the integrated hybrid solar energy. Due to the high self-consumption of energy, integrated hybrid solar energy is suitable for the PHS projects.

KEYWORDS: Pumped Hydro Storage (PHS); energy management; solar energy; Solar-Hydroelectric (SHE)

1. Introduction

Pumped Hydro Storage power plants are hydroelectric power plants aimed at generating additional electricity. The concept of such plants is to pump the reservoir from a lower level to a higher level and then, when needed, release that volume of water back into the lower reservoir. The water is pumped into the upper reservoir during off-peak hours when electricity prices are low and released into the lower reservoir during peak hours when electricity prices are high, resulting in an economic gain. A typical Pumped Hydro Storage (PHS) plant is shown in **Figure 1**.

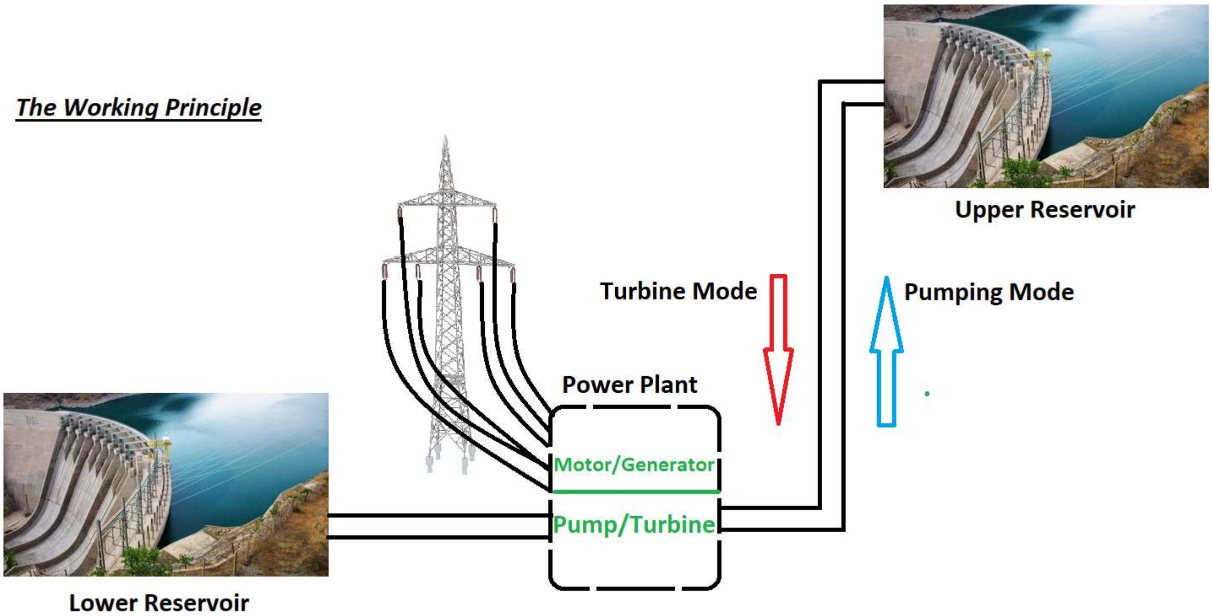

Figure 1. An illustration of Pumped Hydro Storage (PHS) system[1].

The largest share among renewable energy sources is accounted for by hydropower plants. The dams, or storage facilities, are used not only for electricity generation but also for irrigation and flood control. Recently, hydropower plants with pumped storage have been on the agenda in all countries. These plants are considered in the context of physical storage. The aim is to increase the volume of conventional water storage or to make profits by exploiting the price differential between pumping and power generation. Hydroelectric Power Plant (HEPP) systems with pumped storage are used as an alternative to other storage systems. Since battery technology is more expensive to implement and the annual operating cost/renewal cost/battery life isn't what is expected, pumped storage has been chosen, which can be a physical storage method. The table below provides a cost comparison between other storage and pumped storage HEPP facilities. This table is prepared with 2021 indicators by Pumped Hydro Storage International Forum (PHSIF). According to the Pumped Hydro Storage capabilities and costs study of this forum, storage costs are still much higher. Information on storage types and unit costs is provided in **Table 1** below[2].

Table 1. Comparison of energy storage technologies[2].

Costs 2020	PHS	LFP	LAB	Vanad. RF	CAES	Hydrogen
Average power CAPEX (USD/kW)	2,202	3,565	3,558	3,994	1,089	3,117
Average energy CAPEX(USD/kWh)	220	356	356	399	109	312
Average fixed O&M (USD/kWh/yr)	30	8.82	12.04	11.3	8.74	28.5
Effective CAPEX (USD/kW)*	2,910	10,570	11,720	16,170	3,110	8,890

*80 years economic life time, 6% discount rate.

Here PHS stands for pumped storage power plants, LFP for lithium-ion battery storage, LAB for lead-acid batteries, Vanad. RF for vanadium battery storage RF, CAES for compressed air storage, and Hydrogen for hydrogen combined with fuel cells. All the technologies mentioned in the table are methods of energy storage. Pumped Hydro Storage plants are one type of mechanical energy storage, other general methods are electrochemical, thermal, electrical, and hydrogen storage. Each of these types of storage has its own characteristics. When we compare these energy models with each other, we find that they differ in terms of charging/discharging times and size specifications. Thanks to these features, they can be used in different areas. Basically, we can divide the common usage areas into three sections that clarify reserve and response services, transmission and distribution support grids, and bulk power management. Pumped Hydro Storage is the energy storage method that requires the highest charge-discharge time and maximum installed capacity. In **Figure 2** below, all energy storage methods used in detail, and their comparisons between themselves and Pumped Hydro Storage are given[3].

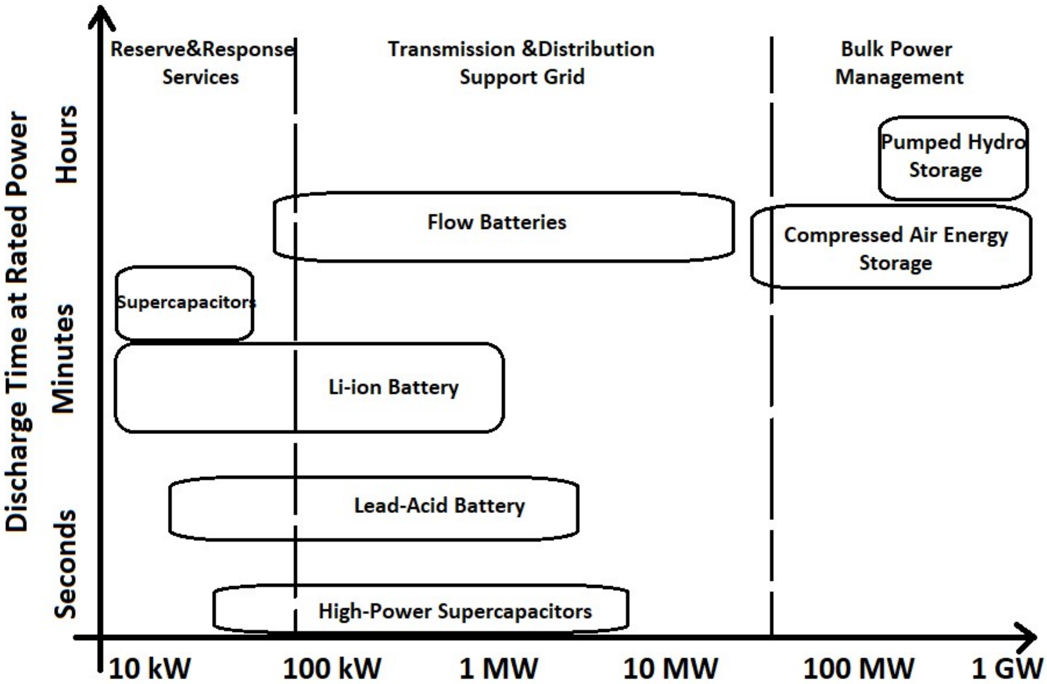

Figure 2. Comparison of the energy storage systems in terms of storage capacity and discharge time[3].

According to the IHA 2022 Status Report, there are pumped storage power plants worldwide with an installed capacity of about 162 GW. The five countries with the highest installed capacity are listed in **Table 2** below[4].

Table 2. Leadership countries for PHS[4].

Countries with Pumped Hydro Storage	Installed Capacity (GW)
China	36.0
Japan	27.5
United States of America	22.0
Italy	7.6
Germany	6.2

Most countries prepare feasibility studies and analyze studies to determine the above pumped storage power plant. In Turkey, feasibility studies for the development of pumped storage power plants have been carried out for a long time, and there is no plant in operation yet. Under the legislation published in the Official Gazette on 12 February 2020, the first step was taken for HEPP with pumped storage. The Gökçekaya PHS, to be completed between 2020 and 2032, will have a total installed capacity of 1.400 MW and is to be completed in Turkish-Japanese cooperation with a value of TL 6.3 billion, according to the legislation that came into force. Türkiye Elektrik İletişim A.Ş. under the coordination of the abolished Electricity Works Survey Administration. (TEİAŞ) and Japan International Cooperation Agency (JICA) under the "Optimal Power Generation Project for Meeting the Peak Demand in Türkiye", which started on 2 February 2010 and was completed in February 2011. HEPP projects were also developed by Tokyo Power Company (TEPCO) experts[5].

Although pumped storage plants are a new challenge for the world, the plants need to be developed in a short time, especially in terms of the supply of energy and water resources, and many studies have been conducted on this mechanism. Rehman et al. evaluated pumped storage technology, the suitability of hybrids, and studies on the islanding of Pumped Hydro Storage systems[6]. Blakers et al. emphasized that pumped hydro energy offers a longer storage time than other battery storage methods[7]. Steffen investigated the application areas of Pumped Hydro Storage for Germany[8]. Ma et al. analyzed the use of pumped storage power plants and battery storage for islands that meet their energy needs from renewable sources[9]. This study is a kind of research article that consists of energy storage technologies, like electrochemical (battery) and mechanical (Pumped Hydro Storage-(PHS)) facilities, for the system in Hong Kong. A case study is performed to clarify the relationship between energy storage systems and the grid. Within the scope of this study, the authors aim to reveal the potential of energy storage systems and lead project sponsors. A comparison of energy storage systems is examined by the levelized cost of energy (LCOE), life-cycle costs (LCC), and LCC ratio methodologies. At the end of this comparison, Pumped Hydro Storage is defined as the optimal solution for the system, with the lowest LCC ratios. Additionally, due to the charge/discharge period of the Pumped Hydro Storage facilities, the system, which is connected to the grid with PHS, is more feasible than the battery option. Yang and Jackson conducted a SWOT analysis of pumped storage power plant use in the United States[10]. Hunt et al. evaluated existing and proposed pumped storage power plants[11]. They emphasized that integrated hybrid energy is a trend, combined with renewable sources like wind and solar energy. The main problem with this synergy is defined as the instability of renewable energy. So, they examined energy storage options in their study. They exhibited the positive and negative sides of the Pumped Hydro Storage facilities. They examined the cost of water storage. Sivakumar et al. studied and projected the long-term use of pumped storage power plants in India[12]. Foley et al. evaluated Pumped Hydro Storage (PHS) that can be operated in the long term with respect to wind energy[13]. They stated that Pumped Hydro Storage facilities are so important for the grid connection. The most compelling part of this investment is the financial structure. So, economic analysis is the vital evaluation of this project. In general, economic indicators like the payback period are taken into account by project sponsors or decision-makers. In this study, they offer to combine Pumped Hydro Storage with wind energy. Pumped Hydro Storage can be used as mechanical energy storage in this mix generation facility. Additionally, a better economic analysis can be obtained from this combined energy system. Javed et al. studied the interoperability of renewable energy sources such as wind, solar, and pumped storage power plants in a hybrid structure[14]. They emphasized that energy storage is the future of energy. They attracted attention to renewable energy penetration. The most optimal solution is offered as solar-wind-Pumped Hydro Storage in their study. This combined energy facility structure is considered preferential basis in terms of economic, environmental, and technical aspects. Within the scope of this penetration, they offered an optimization. Renewable hybrid storage facilities can lead to ongoing alternatives to subsidize the flabbiness of each other and will be up-and-coming areas for the next generation of investigation. Ma et al. studied the feasibility of a hybrid renewable energy structure for an island in a city, including a pumped storage power plant park order[15]. Kusakana studied the optimization of distributed energy systems using pumped storage power[16]. He stated that the electrification system in rural areas is still a challenge. Renewable energy sources are the most promising technologies. However, the flexile generation profile of solar and wind resources, as well as the flexile electricity consumption, restrain these energy systems from being trustworthy without applicable energy storage systems. In general, solar and wind energy are good candidates for the grid structure of a country; however, energy storage systems are not taken into account in this penetration. In this study, a combined structure is designed with wind energy, solar energy, Pumped Hydro Storage, and diesel generators to satisfy the electricity demand. This study aims to reduce the operational expenditure of the system. The demonstration of this structure has been conducted using the MATLAB software program. The proposed simulation model provides a balanced energy structure for the rural area. Barbour et al. studied the international energy value of pumped storage power plants[17]. Lin et al. have worked on a small system of photovoltaic and residential pumped storage[18]. Ding et al. have studied the energy management of a system of wind and pumped storage power[19]. They designed an energy structure combined with wind energy and a pumped hydro structure for reliable prediction of wind energy. In the first step, the mixed integer programming (MIP) formula is used to determine the limitations of the unit total on and off frequencies, as well as the unit among pumping and generating. The designed simulation offers more reliable energy management for wind energy. Javed et al. analyzed a hybrid structure consisting of a battery and pumped storage[20]. Kocaman and Modi conducted a performance analysis for pumped-storage hydro in a hybrid system[21]. Kim et al. studied the operation of air and pumped storage in a hybrid structure[22]. Kapsali et al. focused on an economic analysis of a pumped storage power plant using solar energy[23]. Stocks et al. studied closed-loop systems that provide no outflow, one of the types of pumped storage power plants[24]. Fan et al. prepared a pre-feasibility study for the use of pumped storage power plants at a currently abandoned mine site[25]. Bredeson and Cicilio, reviewed the Pumped Hydro Storage for Alaska region[26]. Baniya et al. stated that the Himalaya is so suitable for pumped storage facilities because of its geographical advantages[27]. Soucek et al. analyzed computational fluid dynamics by using numerical modelling, standards, and scientific literature for Pumped Hydro Storage plant[28]. Hu et al. performed a quantitative study of the liquid behaviour of the manifold in a seawater-pumped storage facility[29]. Wang et al. organized the energy management of a hydropower plant as Pumped Hydro Storage by using other renewable sources[30]. Ghanjati and Tnani analyzed the optimum installed capacity of a hybrid energy facility, including the photovoltaic (PV)/battery/pumped Hydro Storage structure by using artificial intelligence methodology[31]. Lei et al. focused on the operating conditions of Pumped Hydro Storage[32]. They analyzed the adaptability of the vane under the complicated conjuncture of the Pumped Hydro Storage. Lan et al. stated that Pumped Hydro Storage is so important for renewable energy integration. They focused on the transient process of the facility and performed a case study in China[33]. Huang et al. reviewed the selected project site of the Pumped Hydro Storage such as an abandoned mine site. They tried to reveal the heavy metal impact on water and environment[34]. Liu et al. optimized a strategy for the operation conjuncture of Pumped Hydro Storage[35]. Yi et al. indicated that supercapacitors/batteries can be used in biomedical equipment, aerospace, electric vehicles, military industry, transportation industry, and portable electronic equipments[36]. This energy storage systems are used in quick-response technologies. The charge and discharge times of these systems are so short. These technologies can be defined as electronic equipment. Pumped Hydro Storage has so many different project characteristics. Pumped Hydro Storage can be larger than these technologies for mechanical energy storage. Liu et al. clarified the recent development of lithium-ion batteries[37]. This technology is a kind of electrochemical energy storage system. In recent years, lithium-ion battery technology has become the most popular technology in energy storage systems. It can be used as a supportive vehicle for the Pumped Hydro Storage facilities. Ma et al. reviewed the economic life of the supercapacitors under various conditions[38]. These technologies are used in quick-response electronic devices. They have a short charge and discharge period. The cycle of this tool is shorter than that of other energy storage systems. These tools are used in high-tech applications. Previous studies have focused primarily on battery technologies, which are electrochemical energy storage methods, and pumped storage has generally been considered an example of mechanical energy storage. In previous case studies, it was assumed that these mechanical energy storage systems would contribute to the environment and the economy if they were built. In contrast to previous studies, this study evaluated the investment period for pumped storage power plants and examined the conditions required for the construction of this structure. This study demonstrated the conditions under which such a structure can be economically evaluated. In contrast to previous studies, the feasibility of a pumped storage power plant was demonstrated, taking into account the contribution of the integrated hybrid Solar Hydroelectric (SHE) system.

In this study, PHS and the suitability of the solar system for pumped storage power utilization were analyzed. The designed algorithm was used in determining the appropriate size of the solar power plant. The algorithm works with the support of a benefit-cost methodology. The algorithm uses the Matlab database as a data center. The yield resulting from the amount of energy generated in each cycle step is compared to the cost of the system. The purpose with the best proportional result gives the main applicable installed energy amount. It was found that the obtained result of solar hydropower is a support for the proposed pumped storage power plant. There are many methods of energy storage that can be used, given current technologies. Pumped storage power is one of them, as is mechanical energy storage. Although the charging and discharging times of mechanical energy storage systems are much longer than those of other energy storage systems, these systems have advantages in terms of the size of their installed capacity, durability, number of cycles, and maintenance and repair requirements. In this study, it is shown that the planned pumped storage power plant will be more successful if it is supported by integrated hybrid renewable energy. The economic analysis was carried out in assumed scenarios, both alone and with integrated hybrid SHE systems. The main objective of this study is to provide an economic analysis of the conditions under which meaningful pumped storage power can be established. The second objective is to demonstrate the effect of integrated hybrid Solar-Hydroelectric (SHE) systems on energy management and process optimization.

2. Materials and methods

An algorithm is designed for hybrid power optimization. Definitions of algorithm are given in below.

$$Ghyd = \text{ } actual\ electricity\ generation\ of\ the\ PHS \tag{1}$$

$$Gsol = calculated\ electricity\ generation\ of\ solar\ energy \tag{2}$$

$$G\ (x) = \ Ghyd + Gsol\ (x) \tag{3}$$

$$Chyd = \ actual\ cost\ of\ the\ PSH\ energy \tag{4}$$

$$Csol = calculated\ cost\ of\ solar\ energy \tag{5}$$

$$C(x) = Chyd + Csol\ (x) \tag{6}$$

$$P = feed - in - tariff \tag{7}$$

$$B(x) = G(x) \times P \tag{8}$$

$$\text{Loop(x)} = \frac{\text{B}(x)}{C(x)} \tag{9}$$

$$foptimum(x) = \max\ (\text{Loop(x)}) \tag{10}$$

where $Ghyd$ is the realized generation of hydro energy, $Gsol$ is the predicted generation of solar energy, G is the total generation of hybrid facility, x is the repetitive step number, $Chyd$ is the realized cost of hydropower, $Csol$ is the estimated investment cost of solar energy, C is the total cost, P is the feed-in-tariff, B is the benefit value of hybrid system, Loop is the ratio of benefit/cost, $foptimum$ is the optimum point of algorithm function. The optimum point determines the optimal installed capacity of hybrid Solar Power Plant (SPP) part. Designed algorithm is given in **Figure 3** below. This algorithm is not an embedded program, designed by the author for the optimization of the solar energy installed capacity.

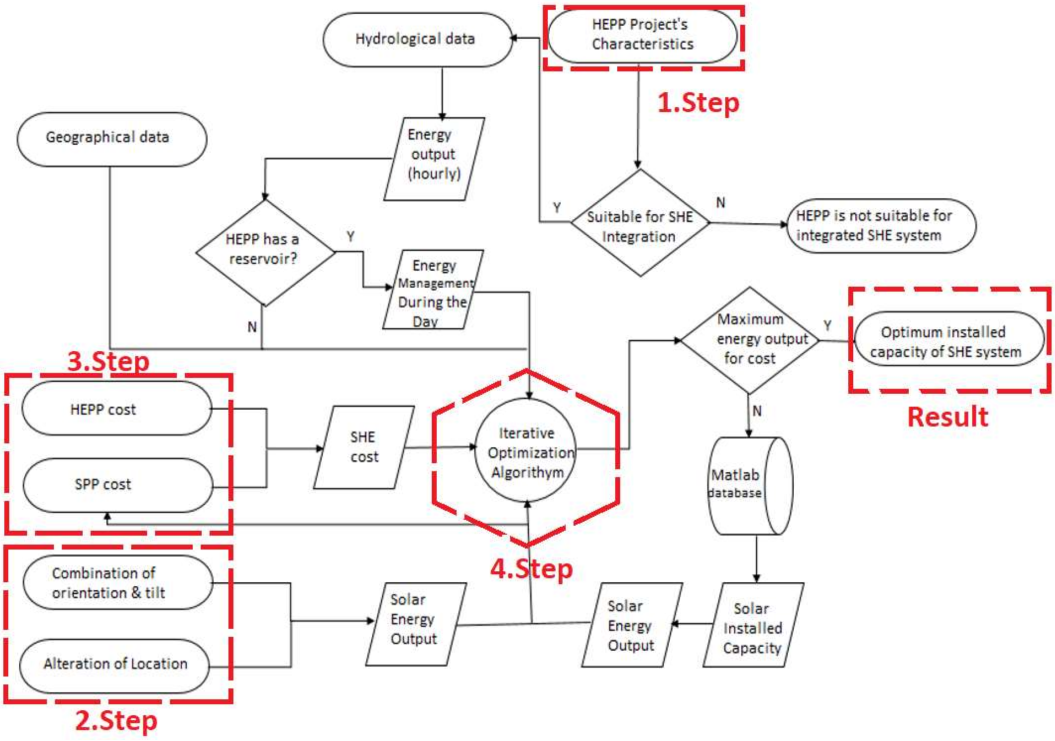

Figure 3. The SHE optimization algorithm.

The algorithm can be clarified as four parts;

- Hydro part of the system (1. Step)
- Solar part of the system (2. Step)
- Cost of the system (3. Step)
- Benefit/Cost cycle of the system-Iteration (4. Step)

The developed algorithm is evaluated based on the benefit-cost methodology. Currently, energy generated by hydropower is supplemented by solar energy, taking into account grid-connected transformer capacity. The algorithm evaluates the solar energy that can be generated without idle capacity, bringing the value to a more reasonable level. The goal of the algorithm is to maximize the benefit achieved per unit. The optimal installed capacity is determined by applying this algorithm to existing hydropower/PHS facilities. PHS consumes power to pump volume from a lower to an upper reservoir. The installed power of the pump that provides the specified amount of consumption is calculated using the following equation.

$$P = \frac{Q \times H \times \rho}{367 \times \eta h} \times ef \quad (11)$$

where P, is the transferred power of pump (kW), Q, is the flow (m^3/h), H, is the height (m), ρ, is the density (kg/m^3), 367 is the conversion coefficient, ηh, is the hydraulic efficiency (%), ef, is the security factor. In general, ηh, is a value between 40-80 % proportions. Security factors can be change according to required power.

3. Results and discussion

A case study examines the economic analysis of pumped storage power plants. The existing Gökçekaya Dam and HEPP plant were used for the case study. Although storage has gained importance in recent years, physical storage is still the most commonly used form of energy storage. Two scenarios are discussed as part of the case study. The results are compared when pumped storage is supplemented with stand-alone and hybrid solar hydropower. When evaluating hydropower with pumped storage alone, the energy needed for the pump is purchased from the grid at lower unit prices. When the same structure is supported by a solar plant, the energy needed for pumping is obtained from the SHE plant. The optimal size of the SHE plant was found considering the prevailing HEPP. The capability that is the subject of the case study can be seen in **Figure 4** below.

Figure 4. The existing hydro power plant demonstration[39]

Project characteristics is given in the **Table 3** below.

Table 3. The hydropower plant project's characteristics.

Projects Characteristics	
Installed Capacity	278,400 kW
Height	115 m
Electricity Generation (2021)	215,000,000 kWh
Capacity Utilization Rate (2021)	8.82 %

Using the data from the Gökçekaya reservoir, the designed algorithm is executed. In the study, the actual power generation for the year 2021 is obtained from the transparency platform of the Istanbul Energy Exchange (EXIST). The algorithm is used to determine the optimal hybrid system, SPP, as a hybrid structure. In addition, two scenarios are carried out for this study. The scenarios are the pumped storage power plant and the pumped storage power plant supported by the hybrid structure. The designed algorithm was applied to the selected Gökçekaya HEPP plant. The assumptions made for the evaluation are listed below:

- The power generation amount of Gökçekaya Dam in 2021 was taken from the transparency platform EXIST. This website is a platform on which the amount of electricity generated is tracked and disclosed to the public by the government[40].
- The grid connection is limited to 278.4 MW for energy generation (278.4 MW is the installed capacity of Gökçekaya Dam and HEPP). This is the legal grid restriction for the facility. Energy generation above this limit value cannot be supplied to the grid. The excess generated energy is interrupted by facility control management before being given to the grid.
- The economic life of the SPP plant is assumed to be 25 years. The stated economic lifetime is the period specified in the datasheets for the First Solar brand PV panels used in the study. The electromechanical equipment of turbines and generators in hydropower plants has a similar economic lifetime. The economic lifetime is a factor that affects the levelized cost of energy (LCOE). The longer this period is, the lower the LCOE[41].
- The installed capacity of the PHS is accepted as 1,400 MW. This installed capacity was officially announced by the government[42].
- The unit cost is assumed to be 857 USD/kW for the SPP facility. The cost of SPP affects LCOE and payback period (PP) calculations. The higher the cost is, the higher the LCOE[43].
- Within the scope of the study, a performance comparison was carried out by analyzing two scenarios.
- In the first scenario, a feed-in tariff is used for the revenue calculation of the PHS.
- In the second scenario, the energy consumption of the PHS is met by a hybrid SPP facility, and this scenario considers an integrated hybrid SHE facility.
- The cost of installed PHS capacity is from the 2021 Pumped Hydro Storage Forum report (2,202 USD/kW) (PHSIF 2021). Under the legislation published in the Official Gazette on February 12, 2020, the Gökçekaya PHS, to be completed between 2020 and 2032, will have a total installed capacity of 1,400 MW and is to be completed in Turkish-Japanese cooperation with a value of TL 6.3 billion. So, 1,046,250,000 USD (equivalent to TL 6.3 billion according to the February 12, 2020 Central Bank forex buying value) is used as an alternative PHS's construction cost. The cost of facilities affects LCOE and payback period (PP) calculations. The higher the cost is, the higher the LCOE and PP[44].
- The amount of power generation from combined hybrid energy is determined by the algorithm. This electricity generation by facilities affects LCOE and payback period (PP) calculations. The higher generation is, the lower the LCOE and PP.
- The payback period calculations assume that the investment is completed in one year and can be commissioned within the next year, according to the assumptions. The longer this period is, the higher the PP.
- The calculation of the payback period was made very roughly; aspects such as Value Added Tax (VAT), taxes, maintenance investments, and depreciation weren't taken into account in the calculation. The additional cost of this expenditure has an adverse impact on LCOE and PP.
- Only revenue and expense differences are considered in the payback period calculation. In this study, the nominal payback period is taken into account. The discount rate has an adverse impact on PP.
- A feed-in tariff is used as the price of electricity generation. This tariff was announced on 1 May 2023 by the government. If the feed-in tariff is low, this situation will affect LCOE and PP calculations adversely[45].

- Electricity sales prices are supported by night, day, and peak unit prices valid for 3 months as of 1.4.2023 announced by Energy Market Regulatory Authority (EMRA). Related prices are given in the table below[46].
- 1 USD equivalent is accepted as 19.7607 TL (18.05.2023 Central Bank Forex Buying). Possible changes in the exchange rate affect, in particular, the prices per unit of goods/price in Turkish lira[47].
- The investment cost of SPP is predicated on the 2021 IRENA renewable energy costs report[42].
- The designed algorithm was run with 45,000 cycles; each step size was taken as 25 kW.
- The 2019 IRENA renewable energy costs report relies on the expense assumptions of renewable energy sources. Within the IRENA renewable energy costs report, it's stated that the annual disbursement for solar energy plants varies between 9.5 and 18.3 USD/kW. For the solar energy plant, 14 USD/kW is accepted because of the unit disbursement. It's stated in the report that the fixed disbursement for hydroelectric power plants is 0.06% of the whole investment cost, and therefore the variable disbursal is 0.003 USD/kWh. In PHS, the identical figures, excluding electricity consumption expenses, are accepted as operating expenses[43]. The higher cost of this operational expenditure has an adverse impact on LCOE and PP. The announced feed-in tariff is given in **Table 4.** The announced energy consumption unit price is given in **Table 5** below.

Table 4. Feed-in tariff.

	Average Price	Price Cap	Base Price
Energy Price for PHS (USDcent/kWh)	10.50	11.55	9.45
Energy Price for Solar Energy (USDcent/kWh)	5.50	6.05	4.95

Table 5. Energy consumption unit price.

	Medium (7 am–6 pm)	Peak (6 pm–11 pm)	Low (11 pm–7 am)
Energy Price (kr/kWh)	281.2067	425.3925	166.4840
Energy Price (USDcent/kWh)	14.2306	21.5272	8.4250

In the second step of the algorithm, the program contains a section on the generation of solar energy. The amount of solar energy used for the internal hybrid energy is determined. The solar radiation and the meteorological data provided by NASA for any point on the Earth. A sample year of original solar radiation data obtained from the official website of NASA is given in **Figure 5** below[48].

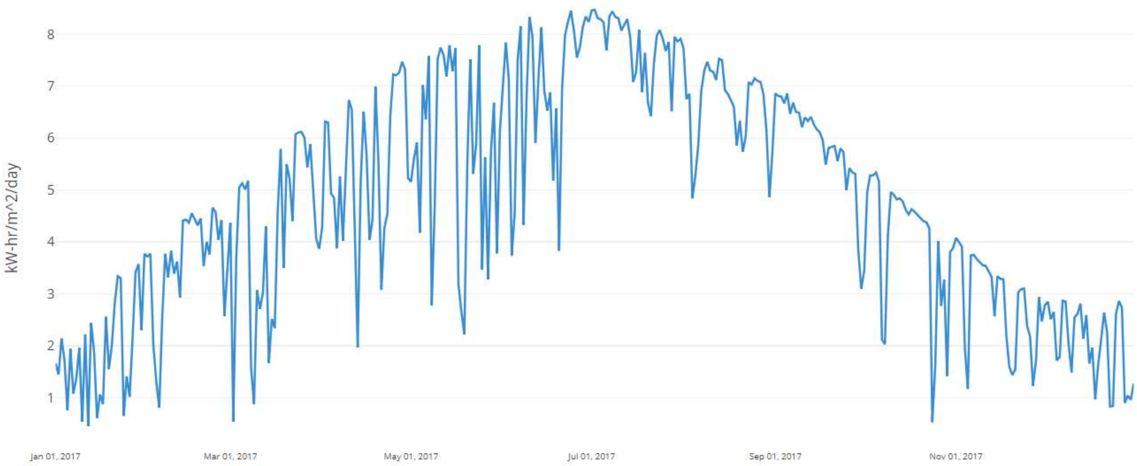

Figure 5. The daily solar radiation obtained from the NASA website (365 days)[48].

The NASA database provides data daily, and solar radiation must be determined on an hourly basis to ensure energy management and optimization of installed power. The two models used when obtaining solar radiation amounts on an hourly basis are the econometric model and the empirical model. While conducting the study, it was decided to use an empirical model for the reasons stated below.

- Ability to convert daily data
- Availability and usage of public data
- The high correlation coefficient
- Prediction of the long-term data

The study, which includes an empirical model, was used to obtain the amount of solar radiation on an hourly basis using MATLAB. In **Figure 6** below, the results obtained for sample days and the amount of solar radiation obtained for the whole year are given. While obtaining the amount of solar energy, the amount of solar radiation on an hourly basis and the current-voltage response of the PV panel to temperature and radiation were used.

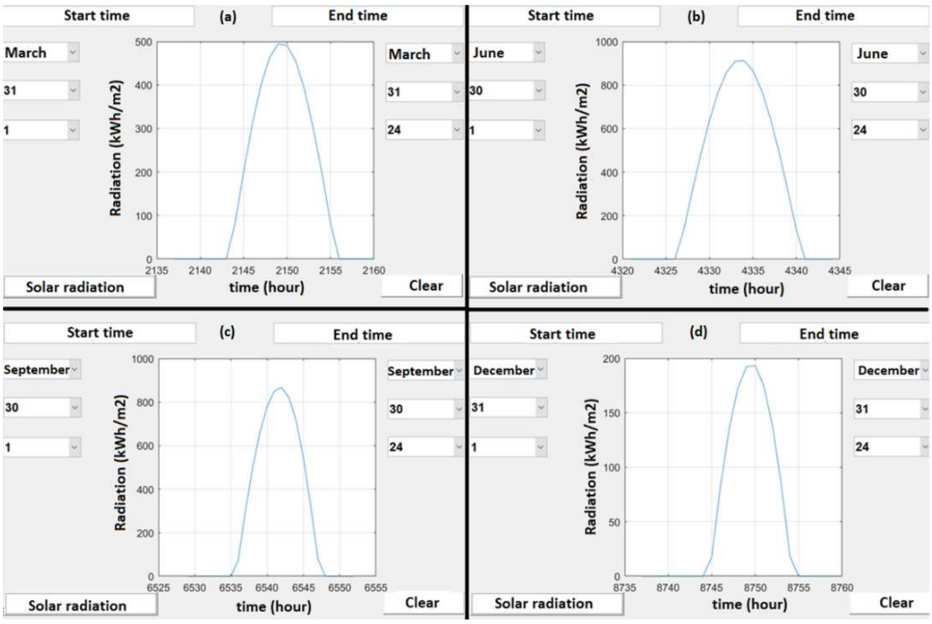

Figure 6. Estimation of the hourly based solar radiation by using the empirical model in Matlab GUI **(a)** 31st March, **(b)** 30th June, **(c)** 30th September and **(d)** 31st December.

The daily radiation amounts were taken from the NASA website for the solar energy plant located within the Gökçekaya HEPP. This original hourly based dataset is given within the **Figure 7** below.

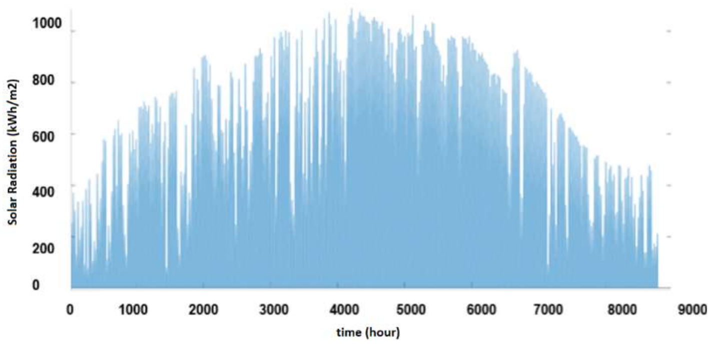

Figure 7. The hourly based solar irradiance obtained from the daily solar irradiance dataset (8760 hours = 24 hours/day × 365 day).

After determining the hourly solar radiation in the selected region, the amount of solar energy is calculated using the designed algorithm. When calculating the solar energy generation, information obtained from the PV data sheet is used. PV data sheet information includes current-voltage information and variations that can be obtained under nominal conditions (1000 W/m^2, AM 1.5, 25 °C) and radiation. The fluctuations are mainly due to temperature fluctuations. The first Solar brand PV panels, model FS-6450, with an installed capacity of 450 watts, were selected for the case study. **Table 6** below contains PV specifications taken from First Solar's official website[41].

Table 6. Nominal values of PV panel.

Model types and ratings at standard test conditions (1,000 W/m², AM 1.5, 25 °C)								
Nominal values		FS-6430	FS-6435	FS-6440	FS-6445	FS-6450	FS-6455	FS-6460
Nominal power	Pmax (W)	430	435	440	445	450	455	460
Efficiency	%	17.4	17.6	17.8	18.0	18.2	18.4	18.6
Voltage at pmax	Vmax (V)	182.6	183.6	184.7	185.7	186.8	187.8	188.8
Current at pmax	Imax (A)	2.36	2.37	2.38	2.40	2.41	2.42	2.44
Open circuit voltage	Voc (V)	219.2	219.6	220	220.4	221.1	222	222.9
Short circuit current	Isc (A)	2.54	2.55	2.55	2.56	2.57	2.58	2.59
Maximum system voltage	Vsys (V)	1,500[5]						
Limiting reverse current	Ir (A)	5						
Maximum series fuse	Icf (A)	5						

Once all the steps specified in the algorithm had been completed, the installed output of the SHE system, which can be implemented as an integrated hybrid system, was determined. Once the contribution of solar energy had been determined, the economic analysis studies began. Taking into account the conditions previously discussed in the "Acceptance" section, the LCOE and payback period were determined as the key indicators. The revenues and costs were calculated according to the specified scenarios. Results are given in **Table 7** below.

Table 7. Evaluation results.

	1st Scenario		**2nd Scenario**	
Evaluation	**PHS**	**PHS+SHE**	**SHE**	**PHS+SHE**
Gökçekaya HEPP installed capacity (MW)	278.4	278.4	278.4	278.4
PHS installed capacity (MW)	1,400	1,400	1,400	1,400
Energy requirement of pumping (MWh)	1,397,500	1,397,500	1,397,500	1,397,500
PHS energy generation (MWh)	1,075,000	1,075,000	1,075,000	1,075,000
PHS investment cost (million USD)	3,082,800	3,082,800	1,046,250	1,046,250
SPP installed capacity (kW)	-	904,500	-	548,775
Total hybrid installed capacity (MW)	1,400	2,304.5	1,400	1,948.775
SPP energy generation (MWh)	-	1,450,369	-	879,962
Net hybrid generation—Consumption (MWh)	−322,500	1,127,869	−322,500	557,462
Hybrid SPP investment cost (million USD)	-	775.16	-	470.30
Annual revenue (million USD)-Feed-in Tariff-Base	101,588	104,205	101,588	101,588
Annual revenue (million USD)-Feed-in Tariff-Average	112,875	115,783	112,875	112,875
Annual revenue (million USD)-Feed-in Tariff-Cap	124,163	127,362	124,163	124,163
Annual revenue (million USD)-Market Peak Price	231,417	231,417	231,417	231,417
Energy cost of pumping (million USD)	117,739	-	117,739	43,603
Annual PHS operational expenditure (m USD)	5.075	5.075	5.075	5.075
Annual SPP operational expenditure (m USD)	-	12.663	-	7.683
Annual hybrid operational expenditure (m USD)	5.075	17.738	5.075	12.758

Table 7. (*Continued*).

	1st Scenario		2nd Scenario	
Evaluation	**PHS**	**PHS+SHE**	**SHE**	**PHS+SHE**
Annual gross cash surplus (million USD)-Feed-in tariff-base	−21.226	86.467	−21.226	45.407
Annual gross cash surplus (million USD)- Feed-in tariff-base	−9.939	98.045	−9.939	56.514
Annual gross cash surplus (million USD)- Feed-in tariff-base	1.349	109.624	1.349	67.802
Annual gross cash surplus (million USD)- Market peak price	108.603	213.679	108.603	175.056
Payback period (year-nominal)- Feed-in tariff-base	-	44.61	-	33.40
Payback period (year-nominal)- Feed-in tariff-average	-	39.35	-	26.83
Payback period (year-nominal)- Feed-in tariff-cap	-	35.19	-	22.37
Payback period (year-nominal)- Market peak price	28.39	18.05	9.63	8.66
Levelized cost of energy-LCOE (USD/kWh)	5.724	3.996	3.829	1.496

$$\mathrm{LCOE(x)} = \frac{\mathrm{INVCost}(x) + (ELxOPEX(x)}{ELxGEN(x)} \quad (11)$$

$$\mathrm{PP(x)} = \frac{\mathrm{INVCost}(x)}{Revenue(x) - OPEX(x)} \quad (12)$$

where $LCOE$, is the levelized cost of energy (USD/kWh), PP, is the nominal payback period of the facility (year). $INVCost$, is the investment cost (USD), EL, is the economic life of the facility (years), $OPEX$, is the annual operational expenditure (USD/y), GEN is the electricity generation of the facility (kWh/y), $Revenue$, is the revenue of the facility (USD/y).

The energy generation from Gökçekaya Dam will be about 215 million kWh in 2021. During the construction of the pumped storage power plant, it was planned to pump the discharge from the lower basin to the upper basin. The pumped storage power plant will be built in the future. Since the pumped storage power plant has the same water flow as the existing Gökçekaya power plant, it can produce 1075 million kWh with an analogous generation profile. It was calculated that a pump with an installed capacity of 1400 MW. In the 2021 calculations, it was determined that the Gökçekaya HEPP would require an energy consumption of approximately 1397 million kWh to pump this reservoir from the lower level to the upper level. In the economic evaluation, it was assumed that the required energy consumption would be covered by relatively low prices for the unit of demand (at night) and that it would be sold during the peak period, which implies a high price for the unit of measurement when selling energy. In addition to this evaluation, feed-in tariff base/average/cap situations are taken into account. In the first scenario, only the PHS was evaluated, and after completing the economic analysis, the investment has a payback period of 28.39 years for the market peak price. Other feed-in tariff options cause meaningless results or long-term payback periods. If the PHS facility is supported by a hybrid solar energy system for internal energy requirements, payback periods can be shortened. In the first scenario, the investment has a payback period of 18.05 years, which is supported by integrated hybrid solar energy. In the second scenario, the PHS investment has a payback period of 9.63 years for the market peak price. The investment has a payback period of 8.66 years, which is supported by integrated hybrid solar energy. The difference in the first and second scenarios is due to the investment cost of the PHS facility. In the first scenario, the size of the plant SPP, which can be installed as a hybrid plant within the existing Gökçekaya dam and the HEPP plant, is optimized using the developed algorithm in addition to the HEPP pumped storage plant. It is shown that a plant SPP with an installed capacity of 904.5 MW (36,180th stage × 25 kW) can be constructed. In the second scenario, it is shown that a plant SPP with an installed capacity of 548.775 MW (21,951th stage × 25 kW) can be constructed. The cost-benefit analysis is shown in **Figure 8** below.

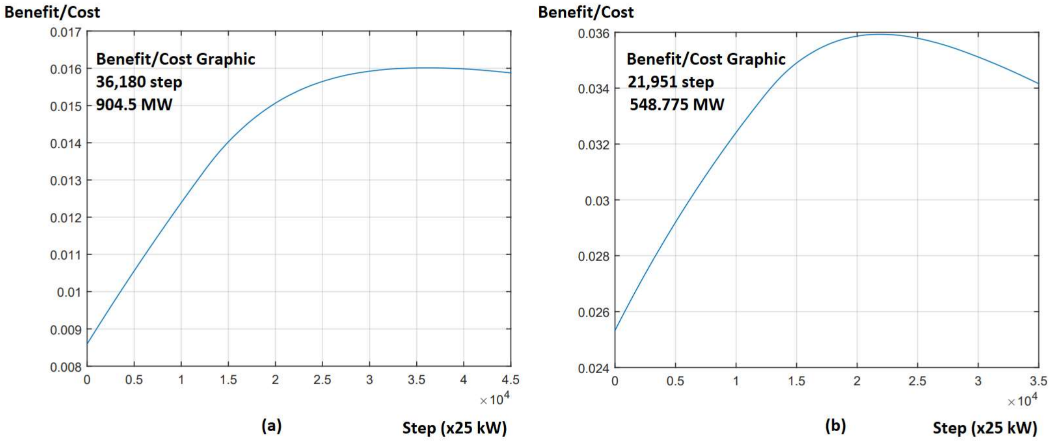

Figure 8. Benefit/Cost graphic of hybrid SHE system **(a)** 1st scenario **(b)** 2nd scenario.

When an evaluation is created to incorporate the pumped-storage HEPP with the contribution of the hybrid SPP structure, it's observed that the second scenario pays back the investment in 8.66 years. During this study, it's assumed that the amount of energy required by the pumped-storage HEPP facility is met by the SPP facility, while the increased energy production is sold during market demand. The daytime demand unit prices supported by sales are the unit prices announced by EMRA and valid for three months as of 01.04.2023. The increases in energy costs experienced in recent months are reflected in unit prices. The best benefit/cost optimization point, SHE system energy amount, and current HEPP/SHE system comparison are given within the graphics in **Figure 9** below.

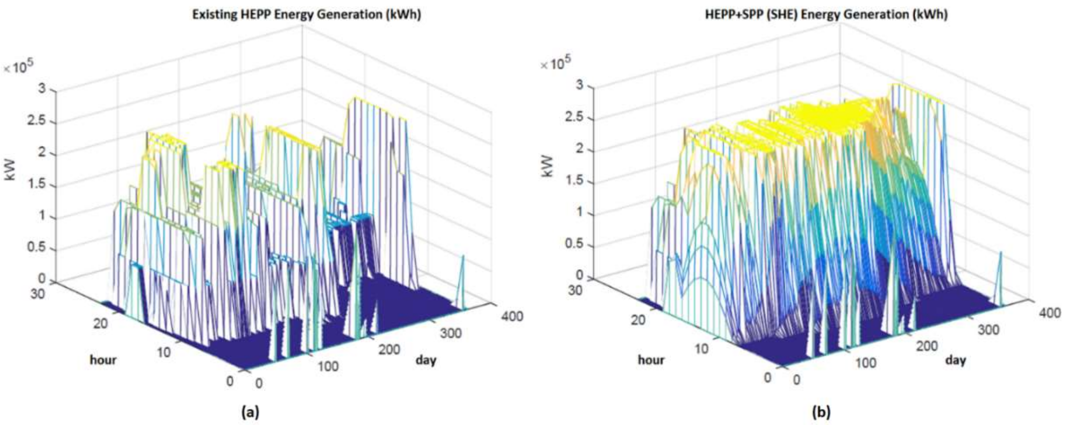

Figure 9. Energy generation comparison of existing HEPP **(a)** and Hybrid SHE **(b)** facilities.

As can be seen in **Figure 9**, the energy generation of the existing HEPP plant is sensitive to climatic and meteorological changes. So, energy management is quite difficult. It also goes without saying that the existing HEPP plant has a low capacity utilization rate for the energy of the facility shown in the graph. A low utilization rate is an indicator of inefficient operation of the plant. In the other graphic, the integrated hybrid structure, it is observed that solar and hydro energy complement each other in terms of energy generation. The generation of the HEPP facility is high in the spring months when the amount of solar energy is relatively low, and the generation of the SPP facility is high during the period when rainfall is low, and these two energy sources complement each other perfectly. This situation leads to more efficient operation of the facility and higher capacity utilization rates. Additionally, the energy efficiency of the transformer is ensured.

4. Conclusion

Pumped storage power plants can provide additional water volume and profits by taking advantage of the energy sales differential between pumping and power generation. Solar hydropower (SHE) is a hybrid structure of solar and hydropower that uses the same electrical infrastructure. In this study, a PHS system with the new feed-in tariff is investigated. In addition, an integrated hybrid solar power system uses an algorithm to achieve optimal installed power. Solar energy is an option for hybrid energy because of its applicability. Two scenarios were discussed in the case study. The difference between the first and second scenarios is due to the investment cost of the PHS facility. Each scenario is evaluated in terms of the base, average, and maximum feed-in price, as well as the market peak price. In the first scenario, only the PHS is examined, and after completing the economic analysis, the investment has a payback period of 28.39 years at a market peak price. In the first scenario, the investment has a payback period of 18.05 years, supported by integrated hybrid solar energy. The economic analysis performed in this assessment assumes that the electricity used for pumping is consumed at low unit prices and that the electricity generated is offered in the market at high prices. The algorithm developed is based on the benefit-cost method. The solar generation profile, compatible with and complementary to the installed profile of the existing hydropower plant when it's low, was determined using the Matlab database. The optimal installed capacity was determined by comparing it with the amount of electricity generated by the sun and the associated investment costs. In the second scenario, it's envisioned that the electricity requirement for pumping will be generated from hybrid solar energy. The electricity consumption required by the pump was covered by solar energy, and the increased solar energy was also fed into the grid at average unit prices (07:00–18:00). Other feed-in tariff options cause meaningless results or long-term payback periods. If the PHS facility is supported by a hybrid solar energy system for internal energy requirements, payback periods can be shortened. In the first scenario, the investment has a payback period of 18.05 years, which is supported by integrated hybrid solar energy. In the second scenario, the PHS investment has a payback period of 9.63 years for the market peak price. The investment has a payback period of 8.66 years, which is supported by integrated hybrid solar energy.

The COVID-19 pandemic and, consequently, the recent and ongoing tensions between Russia and Ukraine have led to an increase in commodity, goods, oil, and energy prices. Accordingly, with a with a feed-in tariff that consists only of pumped hydroelectric storage or is supported by an integrated hybrid solar energy system, no economically viable result can be achieved. The only market price that can be applicable for this investment. If the PHS facility is supported by integrated hybrid solar energy for its internal energy consumption, the results will be more effective. As a result, storage remains a more expensive technology today. It's expected that investment and operating costs per unit will decrease with technological development. However, physical storage is expected to be more sustainable to meet current large-capacity needs. In addition, pumped storage is believed to be a response to warming and the water scarcity expected in the future. As a result of the study, it was found that it's possible to support the pumped storage power plant with a hybrid solar system and market prices if only the storage volume is increased. In addition to this, the feed-in tariff should be determined as a price sufficient to meet the requirement.

Conflict of interest

The author declares no conflict of interest.

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