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Research Article

Optimal Bidding Strategy of a Pumped Hydro Energy Storage Integrated Nuclear Power Plant considering Possible Outage

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Recently, harmful gases emitted into the atmosphere disrupt the balance of nature and cause climate changes. The tendency towards renewable energy is increasing in order to prevent climate change. The importance of the conventional power plants in the power system is maintained due to the intermittent nature of renewable energy sources. In this regard, nuclear power which is one of the conventional power plants takes attention. In this study, a new approach for optimal scheduling of a Pumped Hydro Energy Storage (PHES) integrated Nuclear Power Plant (NPP) system is proposed. It is expected that PHES provides significant economic contribution to the grid operator especially by ensuring energy supply security of the NPP. Two different market types named Day Ahead Market (DAM) and Balancing Market (BM) in Turkey are implemented in the trades by using real electricity prices obtained from Energy Exchange Istanbul (EXIST), which is Energy Market Operator in Turkey. In order to evaluate the effectiveness of the proposed model, seasonal impacts of four different months are also examined in several case studies. Furthermore, sustainability analyzes are conducted considering probability of interruption of the NPP during 8 hours. According to the results, it is observed that promising solutions can be obtained thanks to the integration of the PHES in the presence of the different market types even if outages are planned.

1. Introduction

1.1. Motivation and Background. The rapid increase in the world population has necessitated meeting the large-scale continuous energy demands. This requirement of developed and developing countries can be seen via increased rate of the renewable energy sources besides conventional energy sources. Basically, there are some definitions of the energy in terms of different usage field. Energy can be defined as the ability to do work and can be transformed from one form to another [1]. Economists define the energy as a fuel material, which plays an important role in meeting the demands [2]. In this regard, it can be said that the primary energy sources such as geothermal, natural gas, nuclear, crude oil, hydraulic power plants, coal, wood, plant and animal residues are the energy sources used directly. Nuclear Power Plants (NPP) among the abovementioned sources have become one of the main energy generation facilities that countries prefer to use. Furthermore, nuclear energy takes an attention in terms of reliable, cheap, sustainable, and accessible features compared to other alternatives [3]. Akkuyu NPP, which is currently constructed in Mersin, Turkey, will consist 4 units with a capacity of 1200 MW. It is known that 15-year guarantee is given for the power plant by the Government of the Russian Federation along with the agreement signed on May 12, 2010. Average price of the 50% of the generated energy under guarantee is determined as 12.35 cents per kilowatt-hour excluding value-added tax [4]. It is also known that the dependence on the renewable energy sources is increasing due to the fact that most of the generated energy in the world is provided by the fossil resources. Furthermore, if the energy demand, which rises simultaneously with the population, is not supplied with renewable energy, human life and social welfare will be adversely effected as a result of increased CO_2 emissions and the use of fossil resources [5]. Distribution of energy resources in the world differs between countries. For instance, while uncertainties in the renewable energy can be easily balanced in Romania thanks to the high ratio of hydroelectric power plants, more than 75% of the total generation is supplied by the nuclear power in France [6]. In this regard, use of the energy storage systems gains more importance to meet the energy demand especially at the peak time intervals [7]. There are many studies related to the management of imbalances between supply and demand. Some solutions such as battery energy storage, advanced supply/demand forecasting methods, and Pumped Hydro Energy Storage (PHES) are suggested to prevent the negative impacts of the variable generation sources like wind and photovoltaic power [8]. Also, it can be said that PHES, which is one of these systems, is the most ideal system in terms of techno-economic analysis [9]. PHES has very important advantages thanks to the easy installation and fast load tracking. Furthermore, many benefits such as energy saving, frequency regulation, and reserve services in the case of outages are available as well as sustainability and environmentally friendly features. New reservoirs for PHES are often created around the world. However, sea water is not preferred to use except for the Okinawa PHES. The reason behind is that sea water reduces the efficiency and the life of the equipment by causing calcification and corrosion in the turbines and the pipes [8]. On the other hand, effective and efficient use of the PHES can significantly shave the peak loads in order to ensure integrity of the power system. In this regard, baseload power plants are generally preferred in order to provide the peak powers. It can provide remarkable economic returns by participating in different market models such as Day Ahead Market (DAM) [10]. However, since the technological infrastructure is insufficient in the baseload power plants, hybrid PHES-integrated baseload NPP can be offered as an alternative solution. It is important to maintain the energy balance in the electrical power system in order to provide uninterrupted electricity, and it is known that power control for the supply-demand balance is carried out in the conventional power plants. Although power control can be carried out by the nuclear reactors, this method is not preferred because of the negative impacts of the reactors on the safety and economic conditions. Integration of the NPP and the PHES therefore can be a useful solution to keep the balance against the increasing ratio of the intermittent renewable energy in the electric power grid.

1.2. Literature Overview. There are several works related to the NPP and the PHES approaches. Lee et al. [11] tried to store the energy thermally in the storage system by utilizing the heat in the reactor via secondary steam flow without changing the output power. Furthermore, a stable power system was achieved by creating a cycle between the storage system and the nuclear reactor in the study in which mechanical and thermal storages are evaluated together. Peng et al. [12] analyzed the transition from fossil fuels to the nuclear energy in order to reduce carbon emissions in China. A policy for carbon emissions reduction was established and forward-looking policies were determined with the calculation methods. Although the increment in carbon emissions has been 116% in 9 years since 2005, this increment has decreased to 18% after 2014 thanks to the increasing rate of nuclear energy. Gong et al. [13] investigated an only NPP-based case study and PHES-integrated NPP-based case study in order to shave the peak demands. As a result, it was foreseen that the need for other base power plants and carbon emissions will decrease. Wang et al. [14] observed the stability operation of the power system in the case of hybrid approach of the NPP and the PHES. Talebi et al. [15] tried to obtain the optimal parameters of the Water-Water Energetic Reactor Unit and to minimize the energy losses by using Firefly Optimization method. The irreversible coefficients for all the components were calculated and optimized via current operational parameters. As a result of the study, destruction in the reactor was reduced by 1%, which is significant gain for the high powers. It was also seen that the capacity factor will provide a capacity advantage to the power system thanks to the integration of the NPP and the PHES. Delavaripour et al. [16] examined the security of the supply and the efficiency of the battery storages during the process. Furthermore, the operations of the storage systems with both small-scale wind generation and conventional power plants were investigated in different models. It was very important that they are operated in the electricity markets with the aim of maximum profitability due to the high initial investment costs of the PHES. It was foreseen that arbitrage strategy will provide more profit by using accumulated water at the low price and the low demand time intervals in the DAM where the market clearing price (MCP) is determined [17]. Thus, energy could be traded not only in the DAM but also in the Balancing Market (BM) and the Intraday Market. Also, it was important that the installation area of the PHES has optimal properties due to the high installation costs. The profit that can be made by optimizing different energy portfolios identified, and the obtained energy for each time intervals of the each system was observed in [17]. Various price estimation mechanisms such as Artificial Neural Networks (ANN) were used in the energy markets to maximize the profits. Makhdoomi et al. [18] realized an optimization model for the hybrid operation of the Photovoltaic (PV) and the PHES system. A new Crow Search Algorithm (CSA) version named CSAdif was developed for the optimization, and the impact of the initial reservoir level on the daily operational cost was investigated. When the first and the last level of the upper reservoir were considered as full, the daily operational cost increased by around 31% in the case PV generation drops from high to normal. Similarly, the daily operational cost decreased by around 22% in the case PV generation drops from normal to low. In [19], the prediction of the spot market prices was carried out by using ANN. Also, the results of the mean absolute percentage error were compared with the autoregressive integrated moving average method. As a result, it was seen that the ANN gives more accurate results than the time series model. In terms of the small scale applications, the sustainable based locating method was examined for the PHES systems in order to rank the candidate domains by

Table 1: Comparison of the proposed algorithm with related literature works.

Reference	Multiple market types	NPP	PHES	Cost analysis	Real energy prices	Optimization	NPP/PHES integration	Outage analysis
[11]	✗	✗	✗	✗	✗	✗	✓	✗
[12]	✗	✓	✗	✗	✗	✗	✗	✗
[13]	✗	✓	✓	✗	✗	✓	✓	✗
[14]	✗	✗	✗	✗	✗	✗	✓	✗
[15]	✗	✗	✗	✗	✗	✗	✓	✗
[16]	✗	✓	✓	✗	✗	✓	✓	✗
[17]	✓	✗	✗	✓	✗	✗	✗	✗
[18]	✓	✗	✓	✓	✓	✗	✗	✗
[19]	✓	✗	✗	✓	✗	✓	✗	✗
[20]	✗	✗	✓	✓	✗	✗	✗	✗
[21]	✗	✗	✓	✓	✓	✗	✗	✗
This article	✓	✓	✓	✓	✓	✓	✓	✓

using fuzzy analysis system AHP and ELECTRE III in [20]. It was tested at the eleven sites in the western. Cameroon and Enep, Mbatu-dam, Benakuma, Bamendjin, and Mentchum were recommended among them, respectively. Xingying [21] provided the coordinated operation of the thermal power plants and the PHES, and the changes in the unit cost of the energy were compared. However, the PHES-integrated NPP was not considered, and optimization approach was not implemented. Among the literature studies mentioned above, although the storage system in the nuclear reactors was examined in [11, 16], the cost of the storage systems was ignored, and only mechanical and thermal storage were evaluated. While the contribution of the system to the grid and possible impacts were observed in [15], the power plant operation was not taken into account. Finally, although the market gain of energy trade was not evaluated in [11, 13, 15], and [16], the profit to be made from the trade in the different markets was determined in [17]. Literature gap is also shared with Table 1.

1.3. Content and Contributions. In this article, an optimization-based modeling of the hybrid power plant that consists the NPP and the PHES is proposed. In order to reveal the effectiveness of the proposed model, a series of case studies have been conducted taking into account the different monthly market prices and the operational conditions. The main contributions of the article are as follows:

(1) Arbitrage strategy-based optimization of PHES-integrated NPP in the multiple market types considering real electricity prices is proposed for the first time in the literature.

(2) A possible outage in the reactors of the NPP in the presence of energy storage systems are analyzed also for the first time in the literature.

(3) Real application of the Akkuyu NPP, which is currently constructed in Mersin, Turkey, is taken into account under the seasonal impacts of different months.

The remainder of the article is organized as follows: the overview of the structure and mathematical model are detailed in Section 2. Simulation results and discussions are presented in Section 3. Finally, conclusions are evaluated in Section 4.

2. Methodology

2.1. Overview of the Structure. The schematic diagram of the proposed test system is shown in Figure 1. Optimization determines the market type considering the daily MCP and System Marginal Price (SMP) obtained from the Energy Exchange Istanbul (EXIST). Here, the main energy source is the NPP. The amount of the energy produced in the reactors is either sold directly to the markets considering the hourly different market prices or is stored in the PHES. In this problem, the objective of the optimization is to determine market type and operational benefits such as selling or storing. Also, the hourly average prices of the different seasons are used in order to observe the changes in the profit as a result of the changes in the energy prices depending on the weather conditions. The nominal power generation data of the NPP are determined as 1200 MW per single unit considering the Akkuyu NPP in Turkey. It is assumed that the aforementioned NPP provides constant power like a base load power plant, and it takes 5 days for the power plant to reach full capacity. The proposed system reduces the peak demand and also provides support and benefit to the network operator. Another purpose of the study is to ensure that the deficit power is met by the storage unit for a certain time in case the NPP plans a possible outage. In other words, the PHES installation is designed with the same capacity of the NPP or with the same capacity of a unit of the NPP to meet the demand under outage during 4–8 hours. Furthermore, the relevant equations of the PHES are formed via [22] and hybrid PHES-integrated NPP model is created by utilizing [23].

2.2. Mathematical Formulation. The aim of the proposed model is to provide maximum gain to the power plant operator, to reduce the peak load demand for the network operator, and to sustain the security of the system in the planned outage situations. In this regard, the system is transformed into a mathematical model as follows.

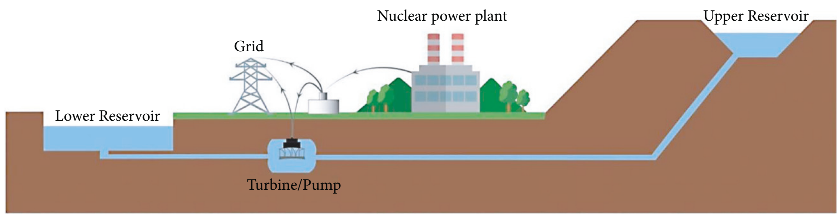

Figure 1: The general design of the proposed model.

2.2.1. Objective Function. The objective is to maximize the total profit. The net profit is the difference between the total gain of the power sold to the DAM and the BM and the total cost of the power bought from the BM. Energy transactions are carried out considering the price of DAM (λ_t^{dam}) and the prices of BM ($\lambda_t^{\text{sold,bm}}$). In (1), the variables are the planned power sold to the DAM ($P_t^{\text{planned,dam}}$) and the power bought from the BM ($P_t^{\text{purchased,bm}}$) and sold to the BM ($P_t^{\text{sold,bm}}$). ΔT is the 1 hour time interval.

$$\max \sum_t \left(P_t^{\text{planned,dam}}.\lambda_t^{\text{dam}}.\Delta T_{\text{dam}}\right) + \left(P_t^{\text{sold,bm}}.\lambda_t^{bm}.\Delta T_{bm}\right) - \left(P_t^{\text{purchased,bm}}.\lambda_t^{bm}.\Delta T_{bm}\right). \tag{1}$$

2.2.2. Power Balance. General power balance of the hybrid system is shown in (2). The sum of the nominal power of theNPP (P_t^{nuclear}), the discharge power of the turbine of the PHES ($P_t^{\text{turbined,ps}}$), and the power purchased from the BM ($P_t^{\text{purchased,bm}}$) must be equal to the sum of the planned power sold to the DAM, the power sold to the BM, and the charge power of the turbine of the PHES ($P_t^{\text{pumped,ps}}$) at each time t.

$$P_t^{\text{nuclear}} + P_t^{\text{turbined,ps}} + P_t^{\text{purchased,bm}} = P_t^{\text{planned,dam}} + P_t^{\text{sold,bm}} + P_t^{\text{pumped,ps}}, \quad \forall t. \tag{2}$$

2.2.3. Pumped Hydro Energy Storage. The power generated by the turbine of the PHES and the power consumed by the pump of the PHES at each time t are given in (3) and (4), respectively. In (5) and (6), the states of the volume of the upper and the lower reservoirs are stated. The amount of the water in a reservoir at time t is equal to the previous volume at time t plus the stored volume and the rainwater minus the used volume and the evaporated water. Constraints (7) and (8) impose a limit on the minimum and maximum level of the lower and the upper reservoirs. The initial volumes of the reservoirs are stated in (9) and (10). The maximum value of the water flow rate is limited in (11) and (12). Constraints (13) and (14) prevent the simultaneous charge and discharge operation of the PHES. The PHES cannot be operated in both pumping and releasing modes at the same time. While both buying and selling from the BM at the same time t are prevented in (15) and (16), it is prevented the plant from acting as a consumer and making arbitrage in (17) and (18). Equalities (19) and (20) state that the amount of the water in the reservoirs at the end of the day is equal to the amount at the beginning of the day. The final water amounts of the reservoirs are limited in (21) and (22) considering the evaporation and the precipitation parameters data in Mersin, Turkey [24]. The final states of the reservoir volumes can change by a maximum of 6% compared to the initial state. The reason behind this is to balance the impacts of the rain and the evaporation on the reservoirs so that the cycle can be continuous. Finally, the maximum power sold to the BM is limited considering transmission capacity in (23). Since the capacity of the transmission lines is 400 MW, the instantaneous power that can be sold is limited to a maximum of 400 MW.

$$P_t^{\text{turbined,ps}} = \sigma^{\text{turbined,ps}}.q_t^{\text{turbined,ps}}, \quad \forall t, \tag{3}$$

$$P_t^{\text{pumped,ps}} = \sigma^{\text{pumped,ps}}.q_t^{\text{pumped,ps}}, \quad \forall t, \tag{4}$$

$$v_t^{\text{UPPER,ps}} = v_{t-1}^{\text{UPPER,ps}} + \left(q_t^{\text{pumped,ps}} - q_t^{\text{turbined,ps}}\right).\Delta T_{bm} + v_t^{\text{rain}} - v_t^{\text{evaporation}}, \quad \forall \text{ if } t > 1, \tag{5}$$

$$v_t^{\text{LOWER,ps}} = v_{t-1}^{\text{LOWER,ps}} + \left(q_t^{\text{turbined,ps}} - q_t^{\text{pumped,ps}}\right).\Delta T_{bm} + v_t^{rain} - v_t^{\text{evaporation}}, \quad \forall \text{ if } t > 1, \tag{6}$$

$$V^{\text{UPPER,ps,min}} \le v_t^{\text{UPPER,ps}} \le V^{\text{UPPER,ps,max}}, \quad \forall t, \tag{7}$$

$$V^{\text{LOWER,ps,min}} \le v_t^{\text{LOWER,ps}} \le V^{\text{LOWER,ps,max}}, \quad \forall t. \tag{8}$$

$$v_t^{\text{UPPER,ps}} = V^{\text{UPPER,ps,initial}}, \quad \forall \text{ if } t = 1, \tag{9}$$

$$v_t^{\text{LOWER,ps}} = V^{\text{LOWER,ps,initial}}, \quad \forall \text{ if } t = 1, \tag{10}$$

$$q_t^{\text{pumped,ps}} \le Q^{\text{max,ps}}, \quad \forall t, \tag{11}$$

$$q_t^{\text{turbined,ps}} \le Q^{\text{max,ps}}, \quad \forall t, \tag{12}$$

$$P_t^{\text{turbined,ps}} \le A.u_t^{ps}, \quad \forall t, \tag{13}$$

$$P_t^{\text{pumped,ps}} \le A.\left(1 - u_t^{ps}\right), \quad \forall t, \tag{14}$$

$$P_t^{\text{purchased,bm}} \le A.u_t^{bm1}, \quad \forall t, \tag{15}$$

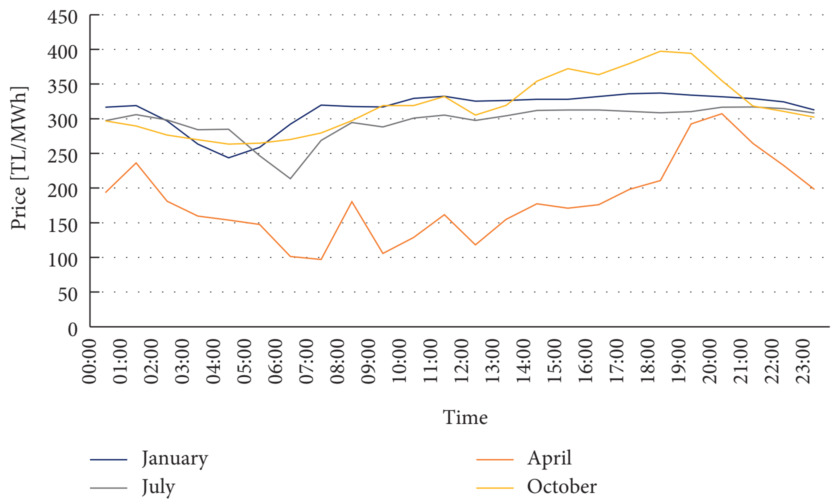

Figure 2: Hourly MCP for each season.

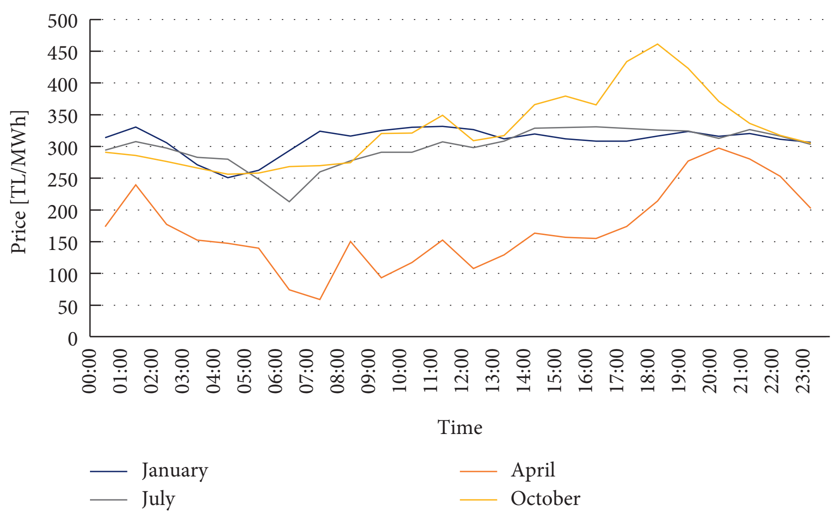

Figure 3: Hourly SMP for each season.

$$P_t^{\text{sold,bm}} \leq A.\left(1 - u_t^{bm1}\right), \quad \forall t, \tag{16}$$

$$P_t^{\text{purchased,bm}} \leq A.u_t^{bm2}, \quad \forall t, \tag{17}$$

$$P_t^{\text{pumped,ps}} \leq A.\left(1 - u_t^{bm2}\right), \forall t, \tag{18}$$

$$v_t^{\text{UPPER,ps}} = V^{\text{UPPER,ps,initial}}, \quad \forall \text{ if } t = 24, \tag{19}$$

$$v_t^{\text{LOWER,ps}} = V^{\text{LOWER,ps,initial}}, \quad \forall \text{ if } t = 24, \tag{20}$$

$$(0.94) \times V^{\text{UPPER,ps,initial}} \leq v_t^{\text{UPPER,ps}} \\ \&9; \leq (1.06) \times V^{\text{UPPER,ps,initial}}, \quad \forall t, \tag{21}$$

$$(0.94) \times V^{\text{LOWER,ps,initial}} \leq v_t^{\text{LOWER,ps}} \\ \&9; \leq (1.06) \times V^{\text{LOWER,ps,initial}}, \quad \forall t, \tag{22}$$

$$P_t^{\text{sold,bm}} \leq 400, \quad \forall \text{ if } t > 1. \tag{23}$$

Table 2: The technical specifications of the PHES.

Parameters	Value	Unit
$V^{\text{LOWER,ps,initial}}$	15000	Hm^3
$V^{\text{LOWER,ps,max}}$	30000	Hm^3
$V^{\text{LOWER,ps,min}}$	3000	Hm^3
$V^{\text{UPPER,ps,initial}}$	15000	Hm^3
$V^{\text{UPPER,ps,max}}$	30000	Hm^3
$V^{\text{UPPER,ps,min}}$	3000	Hm^3
$\sigma^{\text{turbined,ps}}$	0.8	MW/ (Hm^3/h)
$\sigma^{\text{pumped,ps}}$	1.2	MW/ (Hm^3/h)
$Q^{\text{max,ps}}$	1500	Hm^3/h

3. Test and Results

3.1. Input Data. The real energy prices of the BM and the DAM are taken from the EXIST which is Energy Market Operator in Turkey [25]. One day is chosen from January, April, July, and October in order to evaluate the seasonal impacts, and, the selected MCP and SMP prices for each month are depicted in Figures 2 and 3, respectively. Furthermore, the installed power capacity of a unit of the NPP is

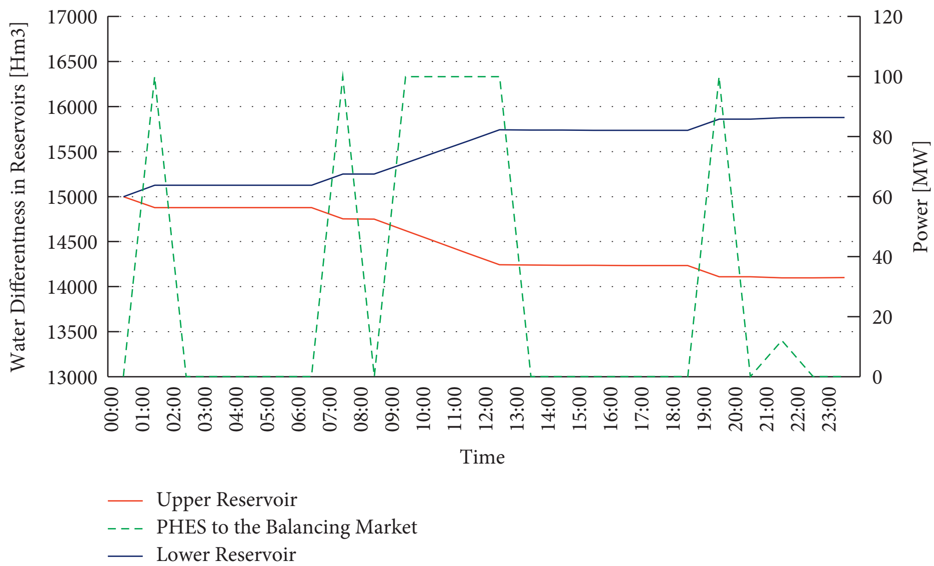

Figure 4: The amount of water in the reservoirs and power sold to the BM by the PHES in January for Case-3.

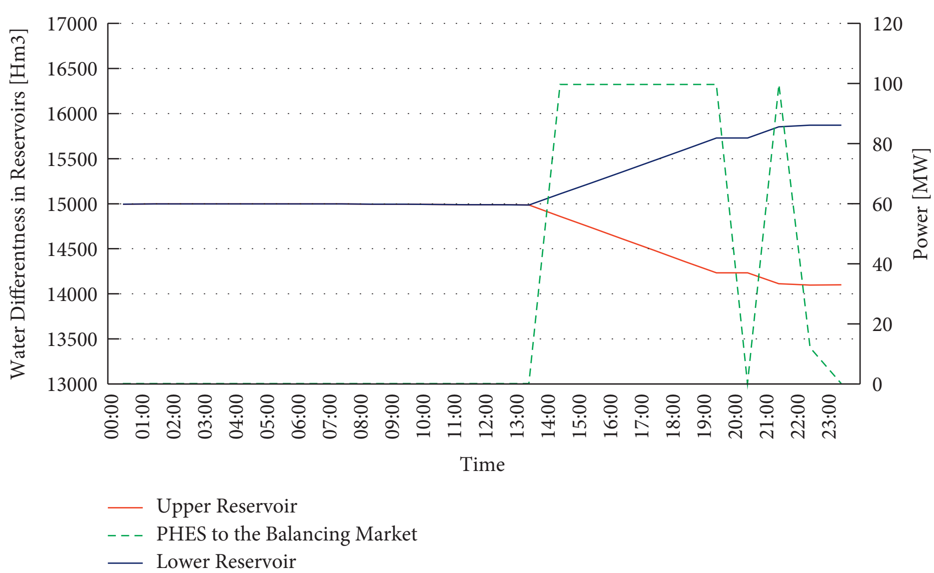

Figure 5: The amount of water in the reservoirs and power sold to the BM by the PHES in July for Case-3.

1200 MW as mentioned earlier. Therefore, the proposed PHES unit is designed so as to provide the 1200 MW along 8 hours in case the NPP plans a possible outage. In this regard, the technical specifications of the PHES are shared in Table 2.

3.2. Simulation and Results. The proposed model is implemented in GAMS [26] v.24.1.3 and is solved using the solver CPLEX. Furthermore, five different case studies are examined to prove the effectiveness of the proposed model as follows:

(i) Case-1: 1200 MW commitment to the DAM without the PHES.

(ii) Case-2: 900 MW commitment to the DAM and 300 MW commitment to the BM without the PHES.

(iii) Case-3: 900 MW commitment to the DAM, and 300 MW commitment to the BM and the PHES.

(iv) Case-4: 900 MW commitment to the DAM, and 300 MW commitment to the BM and the PHES considering possible 8 hours outage.

(v) Case-5: 600 MW commitment to the DAM, and 600 MW commitment to the BM and the PHES considering possible 8 hours outage.

In Case-1, all of the power generated in the NPP at each time interval is sold to the DAM. As a result of this, 9.060, 5.217, 8.535, and 9.178 Million TL is gained in January, April, July, and October, respectively. In Case-2, the power generated in NPP is sold to both the BM and the DAM. The reason for examining this case is to compare the gains with Case-3 in which the PHES unit is integrated. In this regard,

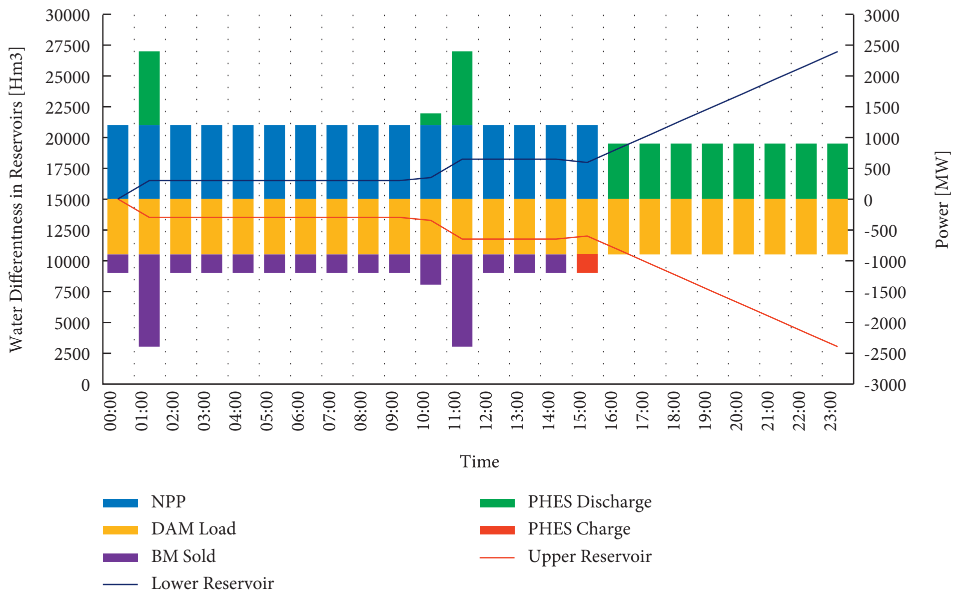

Figure 6: General power balance and the amount of water in the reservoirs in January for Case-4.

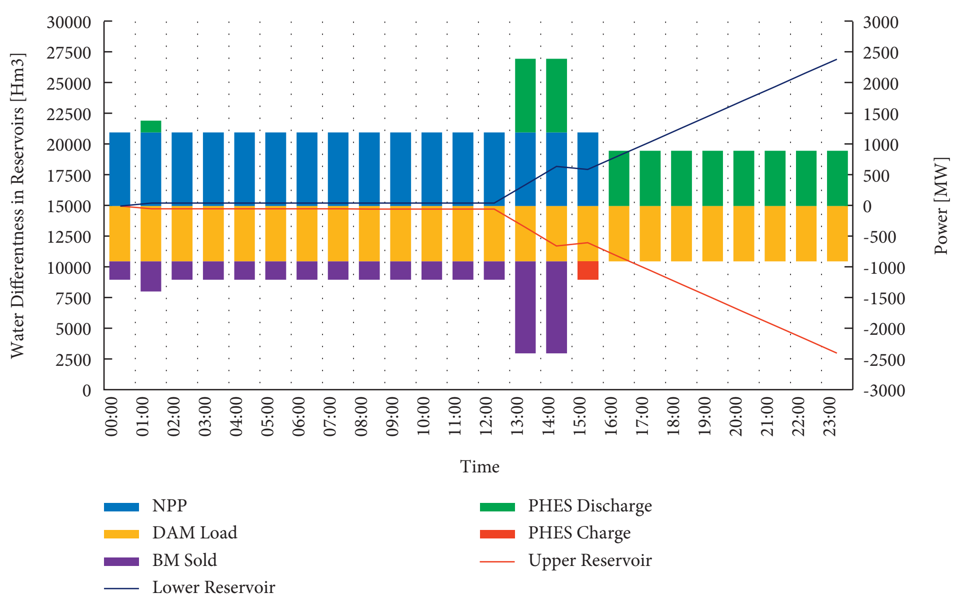

Figure 7: General power balance and the amount of water in the reservoirs in July for Case-4.

900 MW of the 1200 MW power produced in the NPP is sold to the DAM and the remaining 300 MW is sold to the BM. Since the selected months have different prices, it is aimed to increase the revenue of the power plant when the energy prices in the BM are higher than the prices in the DAM and to show the differences in the gains. In this case, the total profits are obtained as 9.026, 5.139, 8.556, and 9.230 Million TL in January, April, July, and October, respectively. There are increment and decrement in the earnings as the prices of each market vary along with the seasons. A decrease in the profits in January and April since the BM prices are lower than the DAM prices and an increase in the profits in July and October since the BM prices are higher than the DAM prices are observed compared to Case-1. In Case-3, some restrictions are included in the model to make the system sustainable. It is assumed that the amount of water in the reservoirs at the end of the day is equal to the amount at the beginning of the day, and a 400 MW limit is imposed on the power to be sold to the BM in order to consider the transmission line capacity. In theory, the amount of the water at the end of the day and at the beginning of the day should be equal. However, they cannot be exactly equal since the evaporation and the rain data in the region are added to the model as a parameter. In terms of sustainability, the amount of water in the reservoirs at the end of the day is therefore limited to a maximum 6% change compared to the beginning of the day. About 900 MW is sold to the DAM in a steady way. Afterwards, 300 MW remaining power is either

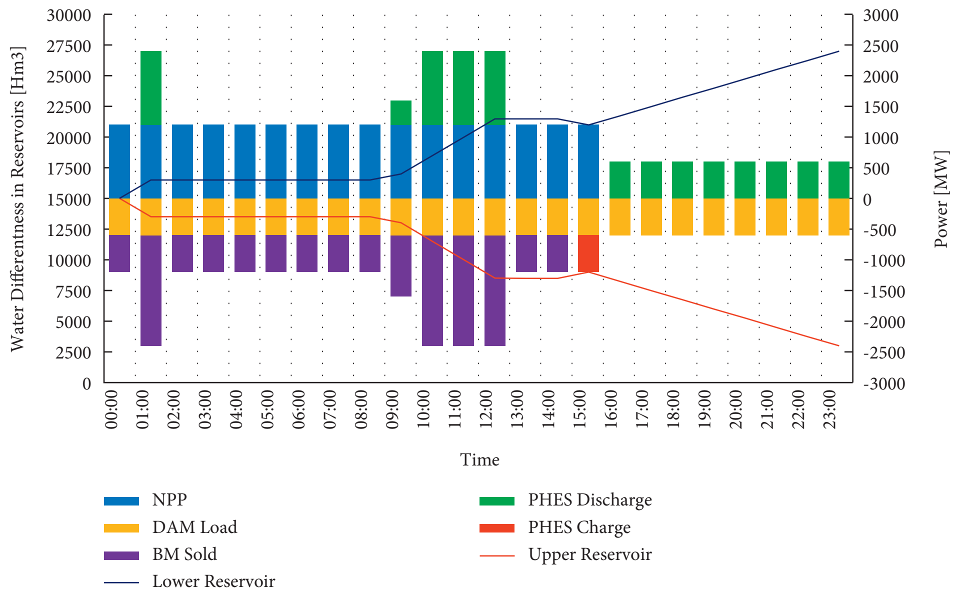

Figure 8: General power balance and the amount of water in the reservoirs in January for Case-5.

stored in the PHES or directly sold to the BM. The amount of the water in the reservoirs and the power sold to the BM by the PHES in January and July for Case-3 are depicted in Figures 4 and 5, respectively. Since the prices vary for each season, the PHES has different scheduling. For instance, SMP reaches the highest value at 01:00, 07:00, from 09:00 to 12:00 and 19:00 in January. Therefore, the PHES sells the power to the BM at these time intervals so as to maximize the profit as can be seen from Figure 4. Since the prices in January have low values, the stored energy is not sold also considering the constraint for the water amount in the reservoirs. Similarly, the PHES does not sell the energy to the BM until 13:00 due to the low price. However, since the price in July is generally higher than the price in January, the discharging operation of the PHES is carried out at from 13:00 to 19:00 and 21:00. Furthermore, it is worthy to note that if all the remaining 300 MW is sold to the BM by the NPP, the PHES can sell only 100 MW to the BM due to the aforementioned line constraint. According to the results of the Case-3, the total profits are obtained as 9.259, 5.347, 8.789, and 9.514 Million TL in January, April, July, and October, respectively.

General power balance and the amount of the water in the reservoirs in January and July for Case-4 are depicted in Figures 6 and 7, respectively. It is assumed that a possible outage in the reactors of the NPP during 8 hours is planned and is observed that the planned DAM power can be met by the PHES even if a reactor shutdowns. Furthermore, there are no reservoir constraints since priority is to provide security of supply and to provide the 900 MW load declared the day before in this case. Therefore, no power is sold to the BM after 16:00, and 900 MW committed to the DAM is compensated. Even though the profits decrease compared to Case-1, sustainability can be maintained without violating the committed power since priority is given to the constant procurement. On the other hand, power sold to the BM in January and July varies due to the different prices as mentioned earlier. While the price in January reaches one of the highest values at 10:00 and 11:00, the price in July reaches one of the highest values at 13:00 and 14:00. Hence, the available power volume of the PHES is evaluated in an attempt to increase the gains until the planned outage. As a result, the total gains are 9.037, 5.098, 8.510, and 9.131 Million TL in January, April, July, and October, respectively.

Finally, the general power balance and the amount of the water in the reservoirs in January and July for Case-5 are shown in Figures 8 and 9, respectively. Similar to Case-4, optimal power allocation of the PHES is evaluated considering a possible outage. However, the committed power to the DAM is reduced from 900 MW to 600 MW in order to observe the impact of the different power allocation ratios on the profits. Although the power sold to the BM increases, it is obtained that the profits for each season reduce as expected due to the decrement in the committed power to the DAM. On the other hand, since priority is given to keep the sustainability of supply as mentioned earlier, the PHES is used as a reserve source during the planned outage. As a result, 600 MW commitment to the DAM is provided by the PHES. In this case, 9.008, 4.840, 8.454, and 8.998 Million TL are gained in January, April, July, and October, respectively.

The total daily profits in different months for each case are shared with Table 3. In Case-4 and Case-5, since the main goal is not only to maximize the gain of the power plant but also to ensure the security of supply of the power system, the increase and the decrease in the profits can be ignored for a special day such as outage planning. There are an increment in the profits in July and October and a decrement in January and April for Case-2 compared to Case-1. The reason behind this is the different market prices between the seasons as mentioned above. About 900 MW of the production is directly sold to the DAM, and 300 MW is directly sold to the BM. Therefore, since an arbitrage strategy cannot be applied

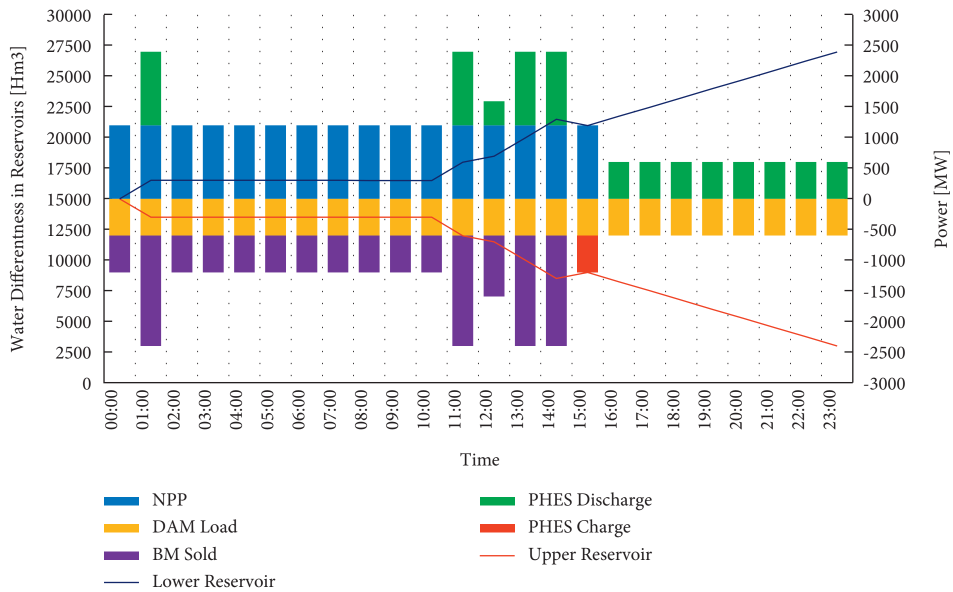

Figure 9: General power balance and the amount of water in the reservoirs in July for Case-5.

Table 3: The daily profits in the selected months for each case.

Profit [million TL]	Case-1	Case-2	Case-3	Case-4	Case-5
January	9.060	9.026	9.259	9.037	9.008
April	5.217	5.139	5.347	5.098	4.840
July	8.535	8.556	8.789	8.510	8.454
October	9.178	9.230	9.514	9.131	8.998

due to the lack of the PHES unit, the profits can only be increased in July and October when the BM price is higher than the DAM price. However, losses in the profits are met thanks to the PHES unit in Case-3. It is achieved that the total profits in each month are increased considering both the flexible management of the PHES and the multi-market structures which have different pricing schemes. Storing the energy in low price time intervals and selling it in high price time intervals provide a very important arbitrage benefit. For instance, while the profit in October for Case-1 is 9.178 Million TL, it is calculated as 9.514 Million TL for Case-3. This provides 336 Thousand TL gain per day, which is a very serious net profit margin.

Finally, it is observed a decrement in the profits due to the scheduled outage as expected. However, this decrement can be negligible for Case-4 compared to Case-1, which can be considered as the base case, because, even if an outage is planned, a possible loss in the profit can be significantly decreased thanks to the flexible management of the PHES and arbitrage strategy under multi-market structure.

4. Conclusion

In this study, optimal scheduling of a PHES-integrated NPP system was proposed considering outage planning under multi-market structure. The model conducted to the real application of Akkuyu NPP, which is the "Build, Operate, Own" agreement signed between Turkey and Russia. The flexible management of the PHES not only provided economic profit to the NPP operator but also minimized a possible loss in the profit in the case of an outage planning for a special day as can be seen from Table 3. It was observed that the total profits vary due to the different market clearing prices of the seasons considering multi-market structure in Case-2. While there was a loss in the profits in January and April, 52 Thousand TL gain per day was earned considering October.

On the other hand, the daily profit for each season was significantly increased in Case-3 by means of the arbitrage strategy compared to a normal operational day in Case-1. Especially, 336 Thousand TL gain per day, which is a very serious net profit margin, in October was achieved. Finally, it was observed that the flexible and the reliable energy managements are provided for the purpose of ensuring sustainability with a minimum profit loss in the case of special outage planning. However, even though there was a decrement in the daily earnings, such a profit loss could be neglected since the priority was given to supply continuity.

In this study, investment and operational costs are not examined in order to observe daily profit and to carry out flexible management under different conditions. Therefore, optimal sizing of the PHES unit considering integration to the NPP will be as a future extension of this work.

Abbreviations

BM: Balancing Market
DAM: Day Ahead Market
NPP: Nuclear Power Plant
PHES: Pumped Hydro Energy Storage
MILP: Mixed-integer Linear Programming

Indices and Sets

$t\,(T)$: Set of time intervals

Parameters

A: Sufficient big positive constant¡
$P_t^{\text{planned,dam}}$: Power planned to be delivered to the grid in the day ahead market at time t [MW]
P_t^{nuclear}: Power produced by the nuclear power plant at time t [MW]
$Q^{\max,ps}$: Maximum flow rate of the water in the turbine/pump model $[Hm^3/h]$
$V^{\text{LOWER,ps,initial}}$: Initial water amount in the lower reservoir $[Hm^3]$
$V^{\text{LOWER,ps,max}}$: Maximum water amount in the lower reservoir $[Hm^3]$
$V^{LOWER,ps,\min}$: Minimum water amount in the lower reservoir $[Hm^3]$
$v_t^{\text{evaporation}}$: Decreased water amount in the reservoirs due to the evaporation $[Hm^3]$
$V^{\text{UPPER,ps,initial}}$: Initial water amount in the upper reservoir $[Hm^3]$
$V^{\text{UPPER,ps,max}}$: Maximum water amount in the upper reservoir $[Hm^3]$
$V^{\text{UPPER,ps,min}}$: Minimum water amount in the upper reservoir $[Hm^3]$
v_t^{rain}: Increased water amount in the reservoirs due to the rain $[Hm^3]$
λ_t^{dam}: The price of energy sold to the day ahead market at time t [TL/MWh]
$\lambda_t^{\text{sold,bm}}$: The price of energy sold to the balancing market at time t [TL/MWh]
$\lambda_t^{\text{purchased,bm}}$: The price of energy purchased from the balancing market at time t [TL/MWh]
$\sigma^{\text{turbined,ps}}$: Coefficient for the water flow/turbine power conversion $[\text{MW}/(Hm^3/h)]$
$\sigma^{\text{pumped,ps}}$: Coefficient for the water flow/pump power conversion $[\text{MW}/(Hm^3/h)]$
ΔT_{dam}: Time resolution for the day ahead market
ΔT_{bm}: Time resolution for the balancing market
$P_t^{\text{turbined,ps}}$: Power produced by the pumped hydro energy storage at time t [MW]
$P_t^{\text{sold,bm}}$: Power sold to the balancing market at time t [MW]
$P_t^{\text{purchased,bm}}$: Power purchased from the balancing market at time t [MW]
$P_t^{\text{pumped,ps}}$: Power pumped to the upper reservoir at time t [MW]
$q_t^{pumpe\ d,ps}$: Flow rate of the water pumped from the lower reservoir at time t $[Hm^3/h]$
$q_t^{\text{turbined,ps}}$: Flow rate of the water released from the upper reservoir at time t $[Hm^3/h]$
u_t^{bm1}: Binary variable for the power change in the balancing market
u_t^{bm2}: Binary variable for the arbitrage in the balancing market
u_t^{ps}: Binary variable for the released and pumped power variation of the pumped hydro energy storage
$v_t^{\text{LOWER,ps}}$: Water amount in the lower reservoir at time t $[Hm^3]$.
$v_t^{\text{UPPER,ps}}$: Water amount in the upper reservoir at time t $[Hm^3]$

Data Availability

The authors have used data of third party, which is the EXIST (Energy Market Operator in Turkey). The data used in the article can be obtained from the website "https://seffaflik.epias.com.tr/transparency/piyasalar/gop/ptf.xhtml."

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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