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RESEARCH ARTICLE

The Combination of Energy Storage and Renewable Energies to Reach a Maximum Profit for Power Systems

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ABSTRACT This paper investigates the effectiveness of the water storage and electricity generation of a pumped-storage hydroelectric plant (PSP) for maximizing total electricity sale revenue of one day as it is integrated into a hybrid power system with the presence of wind power plants (WP) and solar photovoltaic power plants (SP). Four study cases with different rated powers of PSP, including 50, 75, 100 and 125 MW, are implemented to find the most suitable capacity, the optimal hours for water storage and the optimal generation for other hours of the considered PSP. Similarly, the four cases are also investigated for another hybrid power system with the same WP and SP, but PSP is replaced with another conventional hydroelectric plant (CHEP), which does not have a storage function. Five optimization algorithms, including Slime mould algorithm (SMA), Equilibrium optimizer (EO), Jellyfish Algorithm (JS), Coot optimization algorithm (COOT) and War Strategy optimization Algorithm (WSO), are implemented for two hybrid power systems. As a result, EO is the highest performance method with superiority over others in almost all cases. The second hybrid system with PSP can reach a greater revenue than the first hybrid system with CHEP by $31,638, which is about 11% of the total revenue of the first system. In addition, the second system only uses a PSP with a rated power of 75 MW, but the first system must use a higher rated power of 100 MW for CHEP. Clearly, PSP is very effective for hybrid power systems with the integration of renewable power plants in reaching maximum total revenue. However, the comparisons among study cases also indicate that the rated power of PSP should be carefully calculated, otherwise, PSP is no longer applicable.

INDEX TERMS Pumped-storage hydroelectric plant, total electricity sale revenue, conventional hydroelectric plant, hybrid power system, equilibrium optimizer.

NOMENCLATURE

TRE_{1day}	Total electricity sale revenue of one day.
$RE_{S1,h}$, $RE_{S2,h}$	Revenue of System 1 and System 2 at the *hth* hour.
N_w, N_s	Number of wind and solar power plants.
$WG_{w,h}$, $SG_{s,h}$	Generation of the *wth* wind power plant and the *sth* solar photovoltaic power plant at the *hth* hour.
$Price_h$	Price of electricity at the *hth* hour ($/MWh).
PSP_h, $PSPum_h$	Generation and pump power of the PSP at the *hth* hour.
PSP_{Max}	Maximum generation power of the PSP.
$RVolume_h$	Reservoir volume of PSP at the end of the *hth* hour.
$RVolume_{Min}RVolume_{Max}$	Minimum and maximum containment limits of PSP.
Qdc_h	Discharge via turbines in PSP over the *hth* hour.
Qdc_{Min}, Qdc_{Max}	Minimum and maximum discharge limits of PSP.

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PSP_{Min}, PSP_{Max}	Minimum and maximum generation limits of PSP.
η_{PSP}	Efficiency of water storage pump of the considered PSP.
$WS_w^{cut-in}, WS_w^{cut-out} WS_w^{Rate}$	Cut-in, cut-out and rated wind speeds of the *wth* WP.
$WS_{w,h}$	Wind speed at the *hth* hour in the *wth* WP.
WG_w^{Rate}	Rated power of the *wth* WP.
SG_s^{Rate}	Rated generation of the *sth* SP.
SSR_s	Standard solar radiation of the *sth* SP (W/m^2).
$SR_{s,h}$	Solar radiation of the sth SP at the hth hour.
FSR_s	Fixed solar radiation (W/m^2).
UpL, LoL	Upper and lower values of control variables.
G_{pre}, G_{max}	Present iteration and maximum iteration.
dr_1, dr_2	Random values within 1 and 0..
S_{size}	Size of population.
SN_j, SN_j^{new}	The current and new *jth* solutions.
SN_{center}	Center solution of top four solutions.
$SN_{top1}, SN_{top2}, SN_{top3}, SN_{top4}$	Top four solutions of the current population.

I. INTRODUCTION

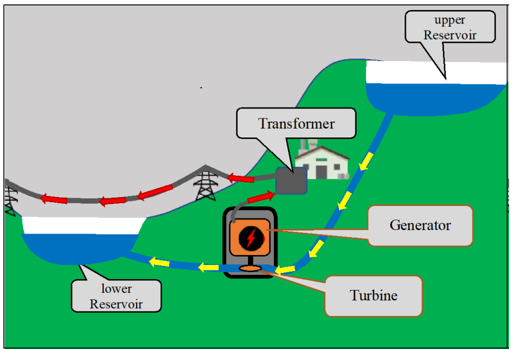
A. MOTIVATION

Balancing demand and supply in fossil fuel-based power systems is simple and is not a serious problem for operators. When demand for loads rises, coal, gas, or oil can be burnt to drive turbines, supplying electricity. So, the systems can be known as "synchronous," i.e., the demand of loads and supply of power plants are synchronized. With renewable power plants (REPPs), the balance becomes a severe problem that must be dealt with. Demand and supply can fall out of sequence. Solar radiation and wind speed-based power plants are "non-synchronous", i.e., their power generation is not fixed by the impact of fluctuations from wind speed and solar radiation. Often, REPPs generate electricity higher than load demand. When this happens, the big challenge is harnessing the surplus power, selling it to other systems where loads need high power, or storing it for other sunless and low wind speed hours [1]. The first solution for surplus energy can benefit REPPs, but it copes with the challenge of signing a contract and high energy loss. On the contrary, the second solution copes with the difficulties of storing energy as higher surplus energy needs higher storage capacity. So, in the study, we suggest pumped-storage hydroelectric plants (PSPs) to store surplus energy and demonstrate that PSPs can bring more benefits to power systems.

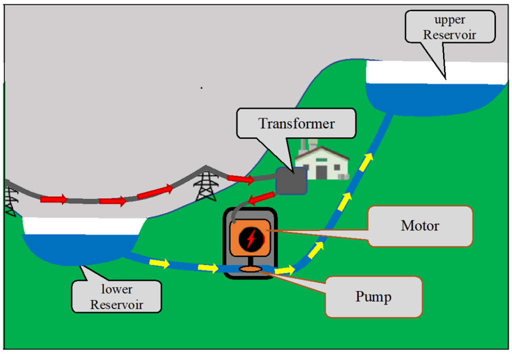
B. LITERATURE REVIEW

In the past decades, hydroelectric plants (HEPs) were combined with thermal power plants (ThPPs) to supply electricity to loads to minimize the cost of fossil fuels such as coal, gas,and oil. Many previous studies supposed that fossil fuels were plentiful over one day or one week, whereas water source from dams was constrained seriously [2]. Hence, the generation process of HEPs was constrained, so hydraulic requirements had to be met precisely. In determining the generation capacity of HEPs, the remaining generation capacity was then assigned to ThPPs, and the cost of burnt fossil fuels had to be cut as much as possible [3]. Different models of HEPs were built, such as constant water head [4] and variable water head [5]. In the constant model of the water head, the generation of HEPs was determined by using discharge through water turbines [6], and the volume of dams could be either neglected [7] or considered [8]. In the variable model of water head, HEPs were separate [9] or a cascaded system with upper and lower dams [10]. The different assumptions of HEPs were integrated into one sole model of ThPPs, which was represented by a fuel cost-generation power function. The studies have proved that ThPPs could reduce their fuel costs thanks to the cooperation of HEPs. Nevertheless, these studies did not concern REPPs, and energy storage was not mentioned in the studies. Latter studies have concerned hybrid power systems with REPPs, such as wind power plants (WPs) and photovoltaic power plants (PVPs) [11], [12], [13]. WPs and SPs were considered in [11] and [12], respectively, while both plants were considered in [13]. Some of the studies supposed renewable energy were predicted exactly, and they used given data to calculate generation [2], [13]. Other studies with opposite ideas considered renewable energy as an uncertainty factor, and they used probability to calculate generation power [14], [15], [16]. On the other hand, the three studies were more complicated than others since they considered a multi-objective function minimizing both total cost and total polluted emission [14], Demand Side Management [15], and electric spot market [16]. However, all the mentioned studies also have the same feature of neglecting the surplus energy from REPPs, and PSPS was not concerned with dealing with the problem.

A typical PSP with two different functions is shown in Figure 1 [1]. The plant has two different reservoirs, a lower reservoir,and an upper reservoir. Usually, the upper reservoir is designed to be larger than the lower reservoir. There are natural inflows to the upper reservoir, whereas the lower reservoir is connected downstream of rivers. Two noted components of the PSP are the generator/motor and turbine/pump. The generator can work as a motor, and the water turbine can work as a pump. If the upper reservoir discharges water through a water turbine, the water turbine runs a generator to produce electricity, and electricity is transmitted to the transmission line thanks to the function of a transformer (see Figure 1a). In another case, the generator acts as a motor to run the pump to move the lower reservoir back to the upper reservoir (see Figure 1b). The particular operation principle of PSP has attracted many researchers over the recent decades. Some of the earliest studies on energy storage considered a simple power system with one pumped-storage hydroelectric plant (PSP) and one thermal power plant (ThPP).They used different mathematical tools to solve the system, such as gradient search algorithm (GSA) [17], evolutionary programming algorithm (EP) [18],and particle swarm optimization algorithm (PSO) [19]. In each study, one sole solution and one sole obtained fuel cost value were reported, and there were no demonstrations of the high effectiveness of the proposed solutions. GSA, a deterministic algorithm, is mainly based on partial derivatives, and it is influenced by the scale and a number of control variables in power systems [20]. Although PSO and EP did not cope with the same shortcomings as GSA, their applications could not reach much better results [21], [22]. So, the implementation of these algorithms ended with a simple power system with one ThPP and one PSP.



a) PSP performs electricity generation



b) PSP perform water storage

FIGURE 1. **Configuration and operation of a typical PSP.**

In recent years, different topics concerning energy storage have been studied and published. Among the studies, power systems with PSPs in countries were solved to reach the highest achievements, such as maximization of electricity sale revenue, minimization of investment cost for designing a power system, and minimization of fuel costs for ThPPs. In addition, power plants in power systems were considered to join the electric spot market to reach the highest revenue. For other applications, sample power systems with IEEE transmission networks were employed to test PSPs and prove the systems' stability. For instance, natural power systems are in China [23], [24], [25], [26], [27], [28], [29], [30], Iran [31], [32], [33], [34], Portugal [35], and Spain [36], [37], while sample tests are an IEEE 14-bus transmission network [38] and a 24-bus transmission network [39].

Among real power systems in countries, China is the top country with the highest number of studies. The study [23] optimally designed a hybrid system consisting of one wind power plant (WP), one photovoltaic power plant (PVP),and one PSP to reduce the cost of initial investment capital but constrain the highest benefit from energy sales. However, the study applied some of the oldest metaheuristic algorithms, such as Genetic algorithm (GA), Simulated annealing algorithm (SA),and PSO. The investment capital could be reduced to 50% as compared to the system without PSP but still reach the same benefit. So, a PSP could be more beneficial for the designed system [23]. The study [24] integrated one 80-MW PSP with one 100-MW WP and one 50-MW PVP, and it could increase to 16% total revenue thanks to the function of the PSP. However, the two studies have not proved that **the** obtained solutions were the best and could satisfy all constraints. In fact, the study [23] used some low-performance algorithms, while the study [24] ignored the applied methods. The study [25] presented the benefits of PSPs in the past (the year 2014) and the present (the year 2017).It proposed an appropriate capacity for PSPs in the future to deal with the vast deviation between the highest and lowest load values. The study has demonstrated that there were many sites to build a system of PSPs as long as the system's total capacity was higher than the present by 1200 megawatts. The study [26] pointed out the same shortcomings of other studies in the past, such as ignoring the model of PSPs and showing operation strategies. So, the study has built a simulation model and implemented a simulation of PSPs in Matlab. Finally, it quantified the optimal parameters of PSPs as the power plants worked in a hybrid system. The study [27] concerned energy transmission and distribution prices in China. So, it proposed a new competitive model for PSPs by joining the electric spot market in China. The new model with three proposed steps was run using the quadratic programming technique (QPT). The study showed the high value of the proposed model since it could lead to a high revenue of 20% for PSPs when renewable energies increased to 8-30%. The study [28] suggested using Mixed-integer linear programming (MILP) to implement the operation of PSPs to reduce the deviation between the highest demand and the lowest demand in a hybrid system. In the study [29], a WP was connected to the north power system in China via a long-distance transmission line to transmit the surplus power at low-demand hours. The connection via the long line led to a high-power loss. So, PSPs were proposed to be installed near the WP to use the surplus power instead of supplying to the north system. Like the idea in the study [29], the study [30] has acknowledged the role of PSPs in long-distance transmission networks. It surveyed the potential of PSPs in different countries. It concluded that power systems in China with long-distance transmission lines were the most effective application of PSPs for taking advantage of REPPs.

Studies of PSPs in Iran and other countries are fewer than those in China. In [31], PSPs were used to save fuel for thermal power plants in Iran for two years. As a result, two hundred million dollars was saved for the period. The study [32] designed two power plants, Khersan I and Khersan II, in the province of Khuzestan, Iran. The study supposed that each designed plant could be either hydropower or storage models. The simulated results indicated that the storage model was more appropriate once it could produce higher energy than the whole system. Unlike other studies, the study [33] proposed using PSPs to meet spinning reserve requirements for power systems with high penetration of PSPs. Wind power curtailment could be lessened using the storage system, and the power system could be more stable. The study [34] applied a Hybrid fuzzy decision-making approach (HFDMA) to design optimal sites of PSPs in the province of Gilan, Iran, by using a fuzzy decision-making method. A part of the power grid in Portugal with the integration of a PSP to WPs and geothermal power plants was studied in [35] for consuming surplus energy from the WPs at high wind speed but low demand hours for storing water. At other hours, with the lack of wind power, the power energy from the stored water could supply the high load demand. Two studies [36], [37] investigated the contributions of energy storage systems to lessening fuel costs and demand of loads for Spanish power systems. The study [36] considered one PSP as a storage system, while the storage system in [37] was a combination of batteries and PSPs in which the capacity of batteries was a very low rate of PSPs. In the study [38], a complicated system considering an IEEE 14-bus grid was supplied by WPs, SPPPs, TPs, and one PSP. Using a two-stage stochastic programming technique (TSSPT), all constraints of electric components in the transmission grid could be exactly met, and total electric generation cost could be lessened by up to 10%. In the study [39], a larger and more complex system with 24 buses, one PSP, one WP,and ten TPs was operated to maximize the system's energy. After one day, energy can be saved up to 50 MWh.

In summary, previous studies substantially contributed to using PSPs to reach higher benefits and better technical factors. However, these studies also cope with shortcomings as follows:

1. The studies [17], [18], [19] solved a very simple system with one PSP and one ThPP for one day with six periods
2. Studies applied low-effective algorithms, such as GSA in [17], EP in [18], PSO in [19], GA, SA, and PSO in [23], QPT in [27], MILP [28], HFDMA [34], TSSPT [38]. Especially, study [24] and other remaining studies have not reported applied algorithms.
3. However, the two studies have not proved that obtained solutions were the best and could satisfy all constraints. In fact, the study [23] used some low-performance algorithms, while the study [24] ignored the applied methods.
4. Studies [23], [24], [25], [26], [29], [30], [32], [34] designed PSPs for real power system, but they ignored real site map.
5. All studies were ignored to clarify the satisfaction of all hydraulic constraints of PSPs.

C. NOVELTY AND CONTRIBUTIONS

In this paper, we bring substantial contributions to power systems about benefits and techniques. In addition, we also tackle several limitations above. We investigate whether a conventional hydroelectric plant (CHEP) or PSP should be integrated with renewable power plants, consisting of wind power plants and solar photovoltaic power plants. CHEP only uses inflows to produce electricity. However, PSP can use the energy from renewable plants to store water and use the stored water to produce electricity at other times. So, the operation of PSP is almost dependent on the generation of renewable power plants rather than using inflows from natural rivers, and the operation of PSP is more complicated than CHEP.

The work in the paper is also a novelty that previous studies still need to clarify. The novelty can be summarized as follows:

1. Develop two hybrid systems and find optimal operation solutions for reaching the maximum total electricity sale revenue for the two systems over one day. The systems have the same two renewable power plants (one WP and one SP) but different types of hydroelectric plants, the first system with one CHEP but the second system with one PSP. The two hydropower plants have the same generation characteristics and hydraulic parameters: generation limits, initial and end reservoir volume, discharge function, reservoir limits and inflows.
2. Consider the same values for the initial and end reservoir volumes in CHEP and PSP. The condition is very important for comparing usefulness between CHEP and PSP when operating in hybrid power systems with many types of power plants. The two plants must use the same available water volume for electricity generation. PSP only produces more power when it consumes power from WP and SP; however, pumping efficiency is only 80%.
3. Investigating four study cases with different rated powers of hydropower plants, including 50 MW, 75 MW, 100 MW, and 125 MW. PSP can run the pump to store water only when the total power from one WP and one SP is equal to or higher than the rated power.
4. Apply five recently published algorithms, including Slime mould algorithm (SMA) [40], Equilibrium optimizer (EO) [41], Jellyfish Algorithm (JS) [42], Coot swarm optimization algorithm (COOT) [43] and War Strategy

Optimization Algorithm (WSOA) [44] for four study cases of the two hybrid power systems.

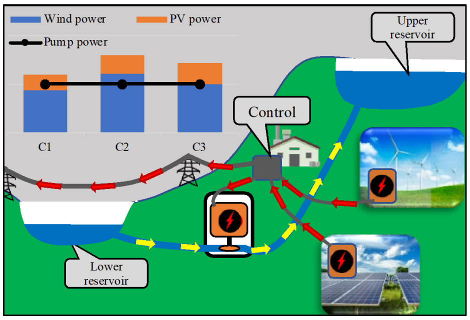
After performing simulation for result evaluation, comparison and discussion, the contributions of the study can be summarized as follows:

1. Find the most effective algorithm among recently published algorithms. As discussed above, previous studies mainly focused on design, benefit and technical factors while they skipped a robust algorithm to reach the best solution. Deterministic algorithms (GSA [17], MILP [28], QPT [27], HFDMA [34] and TSSPT [38]) and ancient metaheuristic algorithms (EP [18], PSO [19], [23], GA [23] and SA [23]) do not own high-performance searchability. Meanwhile, the five applied methods have been proven more effective than many previous or new algorithms in the same years.
2. Find the highest total electricity sale revenue for the two hybrid systems. Two renewable power plants exist, and they can only reach higher revenue as their generation capacity. In fact, the plants only sell electricity as their generation. However, PSPs can consume their energy for water storage and produce electricity for sale with higher revenue
3. Find the most appropriate capacity of PSP and CHEP for the two systems. Both CHEP and PSP have the same characteristic: higher capacity, leading to higher construction investment costs. So, determining a more minor power but reaching a higher revenue is a vast contribution to power systems.
4. Show and prove that PSP is more valuable than CHEP for energy storage and power generation at substantial periods. PSP can store water at hours with low electricity prices and produce electricity at other hours with higher prices. For the same rated power, PSP reaches higher revenue than CHEP for almost all study cases. In addition, PSP with a more minor power also reaches higher revenue than CHEP with a higher power.
5. Prove that all proposed solutions for study cases can meet all PSP hydraulic constraints. For a PSP, different constraints, such as volume of the reservoir, reservoir limits, initial volume and end volume constraints, discharge limits and generation limits, must be considered. If all the hydraulic constraints are not exactly met as required, it cannot make sure the plant is helpful for the hybrid power systems. So, the clarification of constraint satisfaction is essential for a study.

II. PROBLEM FORMULATION

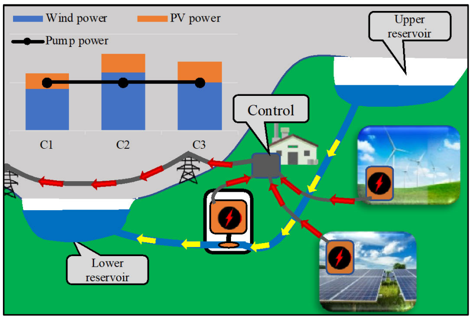
A. DESCRIPTION OF A HYBRID POWER SYSTEM

This study considers the cooperation of PSPs and REPPs for maximizing total electricity sale revenue of one day. The three types of power plants are supposed to be operating in a generation company. The PSP is connected to two other renewable power plants, one WP and one SPP. Figure 2 and Figure 3 summarize the operation of the hybrid power system. In Figure 2, three cases (C1, C2, and C3) have the same feature that the sum of wind power and PV power is higher than pump power, and PSP can run the pump to save water. However, PSP consumes power from wind and PV plants to store water in Figure 2a, but it discharges water to generate electricity in Figure 2b. So, there was a different condition between Figure 2a and Figure 2b. In fact, Figure 2a considers hours with low electricity prices; meanwhile, Figure 2b supposes high electricity prices.



Run Pump

a) Considering hours with low electricity price



Produce electricity

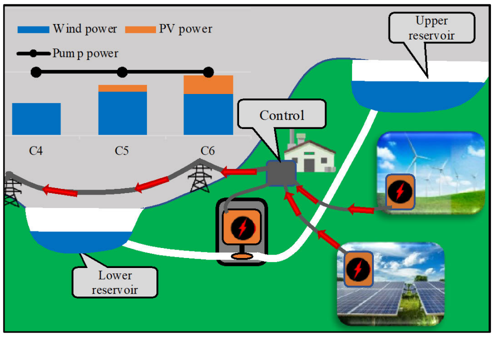
b) Considering hours with high electricity price

FIGURE 2. Operations of PSP for cases with high generation of WP and SP.

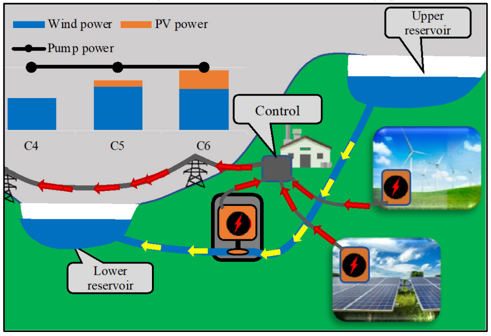
In contrast to Figure 2, Figure 3 considers three opposite cases (C4, C5, and C6), where the sum of wind and PV power is smaller than pump power. However, Figure 3a, considering low electricity prices, does not run generators and pumps; meanwhile, Figure 3b, with high electricity prices, produces electricity. In summary, PSP prioritizes generation for hours with higher electricity prices and water storage for hours with lower electricity prices.

B. MAXIMIZATION OF TOTAL REVENUE AND PUMP OPERATION CONDITION

As joining supply electricity to power systems, the electricity sale price at the *hth* hour $Price_h$ can be informed before, and the generation values in each generation company should be planned optimally to maximize the total electricity sale revenue. Over one operation day, the PSPs are required to keep the water volume equal to the initial available value. So, PSPs can be run as generators to sell electricity or as a pump to store water without electricity sale. At the time that PSPs run as pumps, electricity sale revenue of the company



Stop working
a) Considering hours with low electricity price



Produce electricity
b) Considering hours with high electricity price

FIGURE 3. **Operations of PSP for cases with low generation of WP and SP.**

drops due to the use of energy of PSPs. The challenge of the company is to determine the most appropriate operation for PSPs at each hour so that the total revenue of one day is the highest. This target can be expressed in the formula below:

$$\begin{aligned} &Maximize\ \ TRE_{1day} \\ &= \sum_{h=1}^{24}\left(\sum_{w=1}^{N_w} WG_{w,h}+\sum_{s=1}^{N_s} SG_{s,h}\right).Price_h \\ &+ Price_h.\left(K_h.PSP_h\right) - Price_h.\left(\left(1-K_h\right).PSPum_h\right) \quad (1) \end{aligned}$$

In the equation above, K_h is the operation status of the PSP at the *hth* hour. This factor is 1.0 for generation status and 0 for pump status. As $K_h = 1.0$, generation power PSP_h can be equal to or higher than 0 MWh, but pump power $PSPum_h$ is always zero. For another case (i.e., $K_h = 0$), generation power PSP_h is 0 MWh, and the pump power $PSPum_h$ is equal to a given value (usually, it is equal to the maximum generation). The description of operation statuses regarding K_h can be summarized as follows:

$$K_h = \begin{cases} 1.0, & PSP_h \geq 0 \text{ and } PSPum_h = 0 \\ 0, & PSP_h = 0 \text{ and } PSPum_h = PSP_{Max} \end{cases} \quad (2)$$

However, there is another operation constraint for PSP as it wants to run the pump. In fact, PSP must consume energy from other power plants to start the motor. The motor can be run if the power source is higher or equal to the power of the motor. And in the hybrid system, the total generation of WP and SP is the power source. On the contrary, generation status is not constrained by power condition, but it needs the effectiveness of electricity sale. So, the conditions to set values of either 1.0 or 0 to K_h is based on the following models.

$$K_h = \begin{cases} 0, & \text{if} \left(\sum_{w=1}^{N_w} WG_{w,h} + \sum_{s=1}^{N_s} SG_{s,h}\right) \geq PSPum_h \\ 1 & \text{if} \left(\sum_{w=1}^{N_w} WG_{w,h} + \sum_{s=1}^{N_s} SG_{s,h}\right) \geq PSPum_h \\ 1 & \text{if} \left(\sum_{w=1}^{N_w} WG_{w,h} + \sum_{s=1}^{N_s} SG_{s,h}\right) < PSPum_h \end{cases} \quad (3)$$

The equation above clearly indicates that generation operation is not constrained, but pump operation needs a condition. So, the term "$\left(\sum_{w=1}^{N_w} WG_{w,h} + \sum_{s=1}^{N_s} SG_{s,h}\right).Price_h$" in Equation (1) is the electricity sale revenue for the system, while the second and third terms are not used simultaneously for calculating the revenue of PSP at each hour. If the operation status at the *hth* hour is the generation (*i.e.*, $K_h = 1.0$), the PSP will have a revenue equal to the second term "$Price_h.PSP_h$" and the paid money for the pump will be zero due to the third term "$-Price_h.\left((1-1).PSPum_h\right)$". On the contrary, at another hour h that the PSP runs the pump (i.e., $K_h = 0$), the second term becomes zero, as "$Price_h.\left(0.PSP_h\right)$," but money must be paid as shown in the third term "$-Price_h.\left((1-0).PSPum_h\right)$". The expression is important to calculate the total revenue of the power system in simulation results.

C. CONSTRAINTS OF PUMPED-STORAGE HYDROELECTRIC PLANTS

Used water constraint: In the study, PSPs are integrated into renewable power plants to maximize the total electricity sale revenue. It is supposed that inflows to the upper reservoir are not high, and almost all water for discharge to produce electricity is derived from water storage. So, the generation of the PSPs is mainly dependent on stored water rather than natural inflows from the rivers, and PSPs are subject to the constraint of used water volume. The initial volume and end volume of the upper reservoir must be the same after one day as follows:

$$RVolume_{End} = RVolume_{Initial} \quad (4)$$

In the constraint, $RVolume_{End}$ is the remaining water volume in the upper reservoir after one operation day, while $RVolume_{Initial}$ is the initial available water volume in the upper reservoir. Considering the constraint, the used water volume over one day can be calculated in two ways as follows:

$$Volume_{Used} = \sum_{h=1}^{24} Infl_h + \sum_{h=1}^{24} (1 - K_h)\,.QPump_h \tag{5}$$

$$Volume_{Used} = \sum_{h=1}^{24} Infl_h \tag{6}$$

In the two constraints, $Infl_h$ is the inflow to the upper reservoir over the *hth* hour and $\sum_{h=1}^{24} Infl_h$ is the total inflow to the upper reservoir over one day. $QPump_h$ is stored water by pump over the *hth* hour and $[\sum_{h=1}^{24} (1 - K_h)\, QPump_h]$ is stored water over one day. If the considered PSP can run the pump for one day, Constraint (5) is taken. For another case (i.e., the PSP only produces electricity for one day and does not run the pump for water storage), Constraint (6) is applied. In the study, the two constraints of the used water are investigated to show the effectiveness of water storage. The plant is called PSP as using Eq. (5), and the plant is called CHEP as using Eq. (6).

Constraint of reservoir volume limits: The upper reservoir of the PSP is subject to containment limit constraints. The minimum volume limit is constrained to ensure that the water level is not lower than the dead water head. On the other hand, a maximum volume limit is also imposed on operation conditions for safety. The constraints are as follows:

$$RVolume_{Min} \leq RVolume_h \leq RVolume_{Max} \tag{7}$$

Discharge and generation limit constraints: Water is discharged through turbines, running generators to produce electricity. So, discharge limits are constrained within a predetermined range of generators. A minimum discharge limit guarantees power output not smaller than the minimum generation, while a maximum discharge limit can keep power output not greater than the maximum generation. The limits of discharge are presented by:

$$Qdc_{Min} \leq Qdc_h \leq Qdc_{Max} \tag{8}$$

Generation of the PSP is a function of discharge [17]. So, the limits of discharge also restrict the generation range satisfying the model below:

$$PSP_{Min} \leq PSP_h \leq PSP_{Max} \tag{9}$$

Constraint of water balance in reservoir: In addition to constraints regarding limits of volume and discharge, reservoirs also have another critical constraint associated with approximately all hydraulic factors, such as discharge, inflow, current volume, previous volume, and storage. All these factors are included in the water balance constraint, as shown in the formula below:

$$\begin{aligned} &RVolume_{begin,h} + Infl_h + (1 - K_h)\, QPump_h \\ &\quad - RVolume_h - K_h.Qdc_h = 0 \end{aligned} \tag{10}$$

In Equation (10), $RVolume_{begin,h}$ is the reservoir volume at the beginning of the *hth* hour, and it is also equal to the reservoir volume at the end of the *(h-1)th* hour. The inflow $Infl_h$ and the water storage $QPump_h$ flow to the upper reservoir and make volume greater, so they are added in Equation (10) with "+". On the contrary, discharge Qdc_h flows away from the reservoir, so it gets the sign "-". However, $QPump_h$ and Qdc_h cannot be applied simultaneously in the constraint (10) because the PSP cannot run the pump and generator simultaneously. As shown in Equation (2), K_h is either 1.0 or 0.0, and Equation (10) can be rewritten as the two following equations with the two different values of K_h as follows:

$$\begin{aligned} &RVolume_{begin,h} + Infl_h - RVolume_h - Qdc_h = 0, \\ &\quad with\ K_h = 1 \end{aligned} \tag{11}$$

$$\begin{aligned} &RVolume_{begin,h} + Infl_h + QPump_h - RVolume_h = 0, \\ &\quad with\ K_h = 0 \end{aligned} \tag{12}$$

D. CALCULATION OF WATER STORAGE AND GENERATION

Water storage at each hour h, $QPump_h$ is a constant as running pump of PSP. This parameter has a relationship with maximum discharge and maximum generation of PSP. The pump power and the maximum capacity of generation are the same. However, discharge in the upper reservoir with a high location is flushed down to turbines at approximately the same height as the lower reservoir. However, water storage is pumped from the lower reservoir (low site) to the upper reservoir (high site). Thus, the efficiency of moving water is always smaller than 1.0. Thus, storage water is smaller than discharge, i.e., $QPump_h < Qdc_h$. As the efficiency is known, the water storage is obtained by:

$$QPump_h = \eta_{PSP}.Qdc_{Max} \tag{13}$$

Because both η_{PSP} and Qdc_{Max} are fixed values, $QPump_h$ is also a fixed value for hours with pump operation.

On the other hand, PSP can flush water to generate electricity at hours with generation mode. As discharge is known, the generation can be determined by [45]:

$$PSP_h = \frac{\gamma_2 \mp \sqrt{(\gamma_2)^2 - 4.\,(\gamma_3 - Qdc_h)\,.\gamma_1}}{2.\gamma_1}, \quad h = 1, \ldots, 24 \tag{14}$$

For the case that $\gamma_1 = 0$, PSP_h is obtained by another way as follows:

$$PSP_h = \frac{Qdc_h - \gamma_3}{\gamma_2}, \qquad h = 1, \ldots, 24 \tag{15}$$

E. CALCULATION OF GENERATION FOR RENEWABLE POWER PLANTS

In the study, wind speed and solar radiation are supposed to be given. So, the power plants' generation values can be calculated using the given data. If wind speed is within the cut-in and rated speeds, the generation of wind power plants is a function of rater power, rated speed, cut-in speed, and current speeds. Generation can be zero for other cases with lower speeds than cut-in speed, and generation can reach the rated value for remaining cases. The description of wind power can be written as follows [46]: (16), as shown at the bottom of the next page.

The generation of SP at each hour can be determined by one out of two ways as shown in the following equation [47]:

$$SG_{s,h} = \begin{cases} \dfrac{(SR_{s,h})^2}{(FSR_s.SSR_s)} \cdot SG_s^{Rate}, & (0 < SR_{s,h} < SSR_s) \\ \dfrac{SR_{s,h}}{FSR_s} \cdot SG_s^{Rate}, & (SR_{s,h} \geq SSR_s) \end{cases} \tag{17}$$

III. APPLICATION OF EQUILIBRIUM OPTIMIZATION ALGORITHM FOR THE PROBLEM

A. EQUILIBRIUM OPTIMIZATION ALGORITHM (EO)

EO was first developed and applied for different benchmark functions in 2020. EO was built based on the function of mass balance. This is also a population-based optimization algorithm like Cuckoo search algorithm (CSA) [48], Grey wolf algorithm (GWA) [49], and Tunicate swarm optimizer (TSO) [50], but EO is much simpler than these algorithms. The three algorithms use different ways corresponding to different application conditions for searching new candidate solutions, whereas EO uses one equation to renew current solutions. Furthermore, other algorithms are also more complex since they use a probability function to determine employed updating methods such as CSA [48], GWA [49], and Pollination algorithm (POA) [51]. Opposite to the algorithms, EO uses no condition, and its structure can be summarized as follows.

In the first step, a set of solutions is randomly created as follows:

$$SN_j = LoL + dr_1.(UpL - LoL)\,; \quad j = 1, 2, \ldots S_{size} \tag{18}$$

In the second step, all solutions are evaluated and arranged from the best to the worst quality solutions. From the arrangement, top four solutions are selected and set to SN_{top1}, SN_{top2}, SN_{top3} and SN_{top4}. Then, a center solution of the top four solutions is determined by using the model below:

$$SN_{center} = 0.25.\left(SN_{top1} + SN_{top2} + SN_{top3} + SN_{top4}\right) \tag{19}$$

Before updating a current solution in the population, a solution called SN_{rdtop} is randomly taken from the set of five solutions as follows:

$$SN_{topgroup} = \{SN_{center}, SN_{top1}, SN_{top2}, SN_{top3}, SN_{top4}\} \tag{20}$$

Finally, the *jth* existing solution in the population is updated newly by:

$$SN_j^{new} = SN_{rdtop} + \left(SN_j - SN_{rdtop}\right).T_{Expo} + (1 - T_{Expo})\frac{R_M.T_{Expo}}{dr_2} \tag{21}$$

where SN_{rdtop} is a randomly picked solution from the solution set $SN_{topgroup}$; T_{Expo} is an exponential factor; and R_M is mass production rate. The calculation of T_{Expo} and R_M can be referred to [41].

B. SOLUTION TECHNIQUE TO THE PROBLEM

1) SELECTION OF DECISION VARIABLES

Section Problem Formulation above shows all parameters of the problem. Some parameters are input data; meanwhile, the remaining parameters are variables, which can be set to decision variables or dependent variables depending on the solution method. Different selections can lead to different results, such as valid/invalid obtained solutions and high/low-quality levels of obtained solutions. Invalid obtained solutions cannot satisfy all constraints of the problem, and the use of the solution is canceled. Although valid obtained solutions can exactly meet all constraints, their quality is a key factor in deciding an allowable result. So, analyzing all parameters to select decision and dependent variables is an essential step of the whole search process. The input data of the considered problem are as follows:

1. Wind speeds and wind rated power: WS_w^{cut-in}, $WS_w^{cut-out}$, WS_w^{Rate} and WG_w^{Rate}.
2. Solar radiations and rated power: SSR_s, $SR_{s,h}$, CIP_w and SG_s^{Rate}.
3. Hydraulic parameters: $Volume_{Initial}$, $Infl_h$, $RVolume_{Min}$, $RVolume_{Max}$, Qdc_{Min}, Qdc_{Max}, and η_{PSP}.
4. Electricity price at each hour: $Price_h$.
5. Coefficients of the generation function: γ_1, γ_2 and γ_3.
6. Generation limits of the PSP: PSP_{Min} and PSP_{Max}.

In addition to these input data, the other remaining parameters, consisting of K_h, PSP_h, $PSPum_h$, $RVolume_h$, Qdc_h, and $QPump_h$, are considered as variables. However, only K_h and Qdc_h are decision variables included directly in solutions of algorithms whereas dependent variables are calculated by using the results from the decision variables and formulas in Section Problem Formulation.

To apply algorithms for the problem, there must be upper and lower limits for all solutions, and the limits are given in predetermined ranges of the decision variables. Each particle in each algorithm and the population are, respectively, a candidate solution and a set of candidate solutions. The upper and lower limits for the population are obtained by:

$$UpL = [K_{Max}, Qdc_{max}] \tag{22}$$

$$LoL = [K_{Min}, Qdc_{Min}] \tag{23}$$

where K_{Max} and K_{Min} are, respectively, 1 and 0.

Each solution SN_j is comprised of K_h and Qdc_h ($h = 1, \ldots, 24$ and $h \neq h_{hp}$). h_{hp} is an hour with the highest electricity price, which is determined by using table of electricity price.

2) CALCULATION OF DEPENDENT VARIABLES

As mentioned above, dependent variables are comprised of PSP_h, $PSPum_h$, $QPump_h$ and $RVolume_h$. The determination of the variables is accomplished as follows:

1. $PSPum_h$ is set to PSP_{Max} (see Eq. (2)) if control variable K_h is equal to 0. Then, $QPump_h$ is obtained by using Eq.

(13). For the case, Qdc_h is corrected by setting to 0, and PSP_h is set to 0.

2. $PSPum_h$ is set to 0 (see Eq. (2)) if control variable K_h is equal to 1.0. Then, $QPump_h$ is set to 0. For the case, Qdc_h is used to calculate PSP_h by applying Eq. (14) or Eq. (15).
3. $RVolume_h$ with $h = 1, \ldots, 23$ is obtained by using Eq. (11) if $K_h = 1$, and it is obtained by using Eq. (12) if $K_h = 0$. For the case that $h = 24$, $RVolume_h$ is set to $Volume_{End}$.

In addition to these dependent variables, we have two other dependent variables, including $K_{h_{hp}}$ and $Qdc_{h_{hp}}$. At the hour with the highest electricity price, PSP is forced to generate electricity to sale energy for benefit. So, $K_{h_{hp}}$ is set to 1.0 and $Qdc_{h_{hp}}$ is obtained by:

$$\begin{aligned} Qdc_{h_{hp}} = RVolume_{Initial} &+ \sum_{h=1}^{24} Infl_h \\ &+ \sum_{\substack{h=1 \\ h\neq h_{hp}}}^{24} \left[(1-K_h).QPump_h\right] \\ &- \sum_{\substack{h=1 \\ h\neq h_{hp}}}^{24} (K_h.Qdc_h) - RVolume_{End} \end{aligned} \tag{24}$$

Because of $RVolume_{End} = RVolume_{Initial}$, the equation above can be rewritten as follows:

$$\begin{aligned} Qdc_{h_{hp}} = \sum_{h=1}^{24} Infl_h &+ \sum_{\substack{h=1 \\ h\neq h_{hp}}}^{24} \left[(1-K_h).QPump_h\right] \\ &- \sum_{\substack{h=1 \\ h\neq h_{hp}}}^{24} (K_h.Qdc_h) \end{aligned} \tag{25}$$

Finally, $PSP_{h_{hp}}$ is obtained by substituting $Qdc_{h_{hp}}$ to Eq. (14) or Eq. (15).

3) CALCULATION OF FITNESS FUNCTION

Fitness function of each solution SN_j is denoted by Fit_j and obtained by:

$$\begin{aligned} Fit_j = -TRE_{1day} + PF_{RV}.\sum_{h=1}^{23} (\Delta RVolume_h)^2 \\ + PF_{Qdc}.(\Delta Qdc_{h_{hp}})^2 \end{aligned} \tag{26}$$

where PF_{RV} and PF_{Qdc} are penalty coefficients for the reservoir volume and discharge. $\Delta RVolume_h$ is the violation interval between the hth hour reservoir volume and the upper/lower limit; and $\Delta Qdc_{h_{hp}}$ is violation interval between the $h_{hp}th$ hour discharge and upper/lower limit. $\Delta RVolume_h$ and $\Delta Qdc_{h_{hp}}$ are obtained by:

$$\Delta RVolume_h = \begin{cases} 0 \quad if\ RVolume_{Min} \leq RVolume_h \\ \quad \leq RVolume_{Max} \\ (RVolume_h - RVolume_{Min}) \\ \quad if\ RVolume_h < RVolume_{Min} \\ (RVolume_h - RVolume_{Max}) \\ \quad if\ RVolume_h > RVolume_{Max} \end{cases} \tag{27}$$

$$\Delta Qdc_{h_{hp}} = \begin{cases} 0 \quad if\ Qdc_{Min} \leq Qdc_{h_{hp}} \leq Qdc_{Max} \\ (Qdc_{h_{hp}} - Qdc_{Min}) \quad if\ Qdc_{h_{hp}} < Qdc_{Min} \\ \left(Qdc_{h_{hp}} - Qdc_{Max}\right) \quad if\ Qdc_{h_{hp}} > Qdc_{Max} \end{cases} \tag{28}$$

C. APPLICATION OF EO FOR MAXIMIZATION OF TOTAL REVENUE

The implementation of EO for reaching the highest total revenue of the hybrid power system with PSPs can be summarized in Figure 4.

IV. NUMERICAL RESULTS

In this section, we implement five metaheuristic algorithms consisting of Slime mould algorithm (SMA) [40], Equilibrium optimizer (EO) [41], Jellyfish algorithm (JS) [42], Coot swarm optimization algorithm (COOT) [43] and War strategy optimization algorithm (WSO) [44] for two hybrid power system with four study cases for each. For each study case of each system, each algorithm is run for 50 optimal solutions. Simulation is executed on Matlab program language and computer with a processor of 2.4 GHz and a RAM of 8 GB. The two test hybrid systems and results are presented in the following sections.

A. ANALYSIS ON TWO APPLIED HYBRID POWER SYSTEMS

This study investigates the total electric sales revenue for one day of two hybrid power systems with the same wind power plant and solar photovoltaic power plant but different hydropower plants. A conventional hydroelectric power plant (CHEP) with only a generation function is considered in System 1, while PSP with both generation and pump functions is included in System 2. The two power systems are shown in Figure 5.

The power systems consider a WP with a rated power of 120 MW [52] and a SP with a rated power of 50 MW. For the WP, WS_w^{cut-in}, $WS_w^{cut-out}$ and WS_w^{Rate} are, respectively,

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$$WG_{w,h} = \begin{cases} 0 \quad (WS_{w,h} < WS_w^{cut-in} or WS_{w,h} > WS_w^{cut-out}) \\ WG_w^{Rate} \times \frac{(WS_{w,h} - WS_w^{cut-in})}{(WS_w^{Rate} - WS_w^{cut-in})}, \quad WS_{w,h} \in [WS_w^{cut-in}, WS_w^{Rate}] \\ WG_w^{Rate} \quad WS_{w,h} \in [WS_w^{Rate}, WS_w^{cut-out}] \end{cases} \tag{16}$$

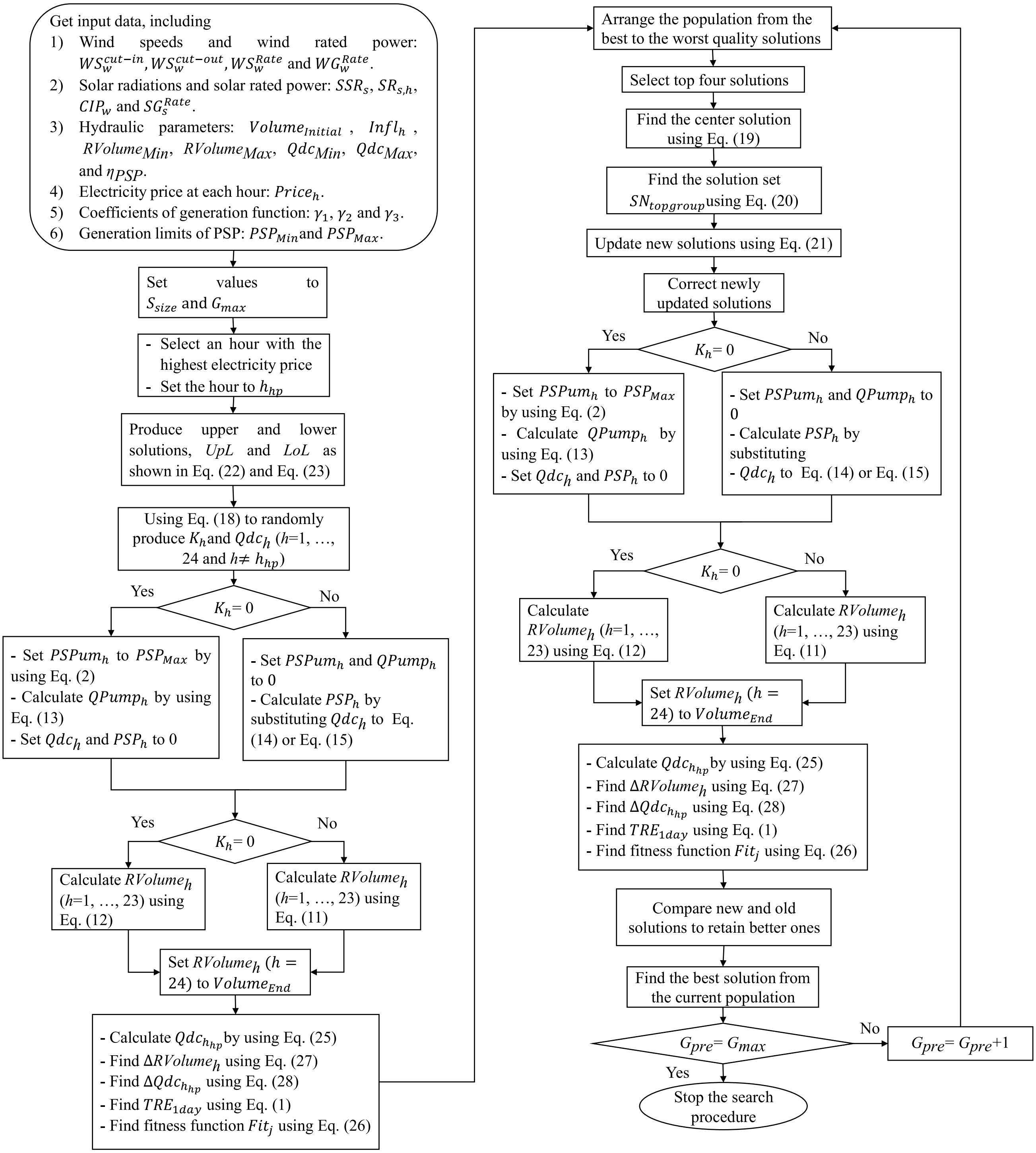
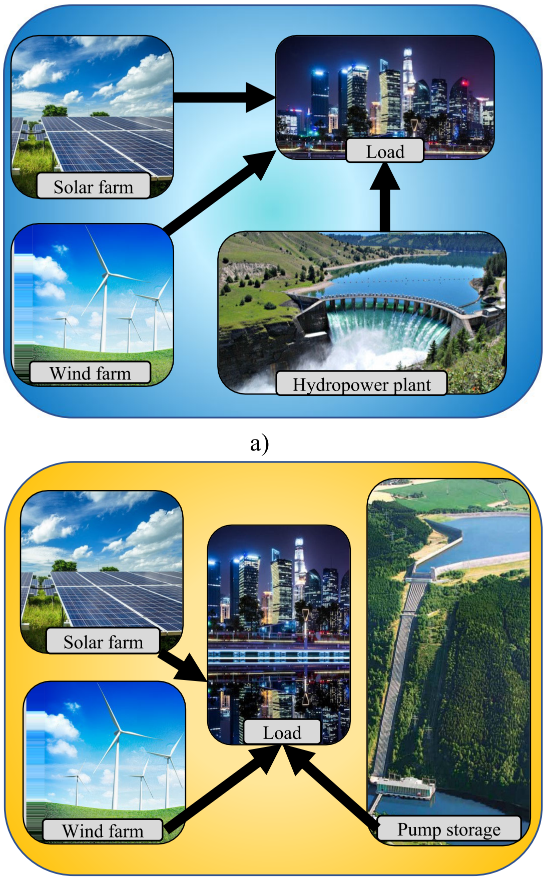


FIGURE 4. The implementation of EO for maximizing total revenue of the considered hybrid system.

5, 45 and 15 (m/s). FSR_s and SSR_s are, respectively, 1,000 W/m^2 and 150 W/m^2, while $SR_{s,h}$ is taken from Table 2 in [47]. Applying Eq. (15) and Eq. (16), power output of the WP and SP at each hour is obtained and then plotted in Figure 6. In addition, the electricity sale prices for the power system [53] are also considered for hours.

The study implements four cases with different rated powers of CHEP and PSP, including 50, 75, 100, and 125 MW to find the most suitable power. The four selected rated powers are based on the maximum total power of wind and solar photovoltaic power plants. From Figure 6, the highest total generation of the two REPPs is about 160 MW at hour 11, and



a)

b)

FIGURE 5. Configuration of two applied systems; (a) System 1 with the presence of CHEP; (b) System 2 with the presence of PSP.

the mean of total generations is about 112 MW. Compared to the maximum total power of 160 MW, the rated powers of 50, 75, 100, and 125 MW are approximately equal to 31%, 47%, 62% and 78%, respectively. As compared to the average total power of 112 MW, the rated powers are approximately equal to 45%, 67%, 89%, and 111%. To clarify the four study cases, we explain the rated power and operation of CHEP and PSP as follows:

1. CHEP: The conventional power plant can only run the generator to produce electricity. The plant's power output can be from the minimum value (0 MW) to the maximum value (the rated power shown in Table 1). The plant cannot work as the upper reservoir has less water than the limited water level. In addition, the plant's generation and produced energy depend entirely on natural inflows. The maximum discharge of the plant (Qdc_{Max}) can be seen in Table 1.
2. PSP: The modern power plant has two functions: running a pump to store water and driving a generator to produce electricity. Like CHEP, PSP can produce electricity from 0 MW to the rated power. However, the pump function is not flexible once only consuming power and stored water are constants. The pump power is always equal to the rated generation power (see Eq. (2)); meanwhile, the stored water is always equal to ($\eta_{PSP}.Qdc_{Max}$) (see Eq. (13)). The maximum discharge of the plant is equal to that of CHEP. However, the pumped water ($QPump_h$) is smaller, as calculated in Table 1.

TABLE 1. Two applied systems and four study cases for each.

Study case	Rated generation power (MW)	η_{PSP} of PSP	Qdc_{Max} of CHEP and PSP (arce-ft/hour)	$QPump_h$ of PSP (arce-ft/hour)
Case 1	50	0.8	110	88
Case 2	75	0.8	160	128
Case 3	100	0.8	210	168
Case 4	125	0.8	260	208

In addition, coefficients of discharge function and inflows of CHEP in System 1 and PSP in System 2 are also given in Table 4 and Table 5 in Appendix. The power output of WP and SP at each hour, the rated generation power selections, and the hourly electric price are also plotted in Figure 6. Figure 6 shows the difference among the four considered cases for running generation and pump of PSP. The black line of Case 1 and the yellow line of Case 2 are below the top of all wind power bars in blue. The red line of Case 3 is below the top of the blue bars and orange bars at hours 2, 6, 8-17, 20, and 21. The green line of Case 4 is only below the top of the orange bars at hours 10-15. The description shows that the PSP can choose every hour to run the pump for Case 1 and Case 2. However, the pump running hours are limited for Case 3 and especially for Case 4. PSP can run the pump at hours 2, 6, 8-17, 20 and 21 for Case 3, and hours 10-15 for Case 4.

B. OBTAINED RESULT FOR SYSTEM 1

In this section, the results of System 1 are presented and discussed. For each case, the population is set to 25, but the iteration number is set to four values, including 50, 100, 150 and 200. Each method is implemented for 50 runs for each value of iteration number and population. There are (4 × 50=200) runs for each applied method and (200 × 5=1,000) runs for five applied methods in each case, and (1, 000 × 4=4,000) runs for five applied methods in four cases. Each run is corresponding to one convergence characteristic, and there are 4,000 convergence characteristics for the whole simulation results of the system. Clearly, the simulation results regarding the convergence characteristics in the system are extremely vast. So, the results in detail are not reported but the best result of each applied method for each setting of iteration number can be reported and shown in Figure 7.

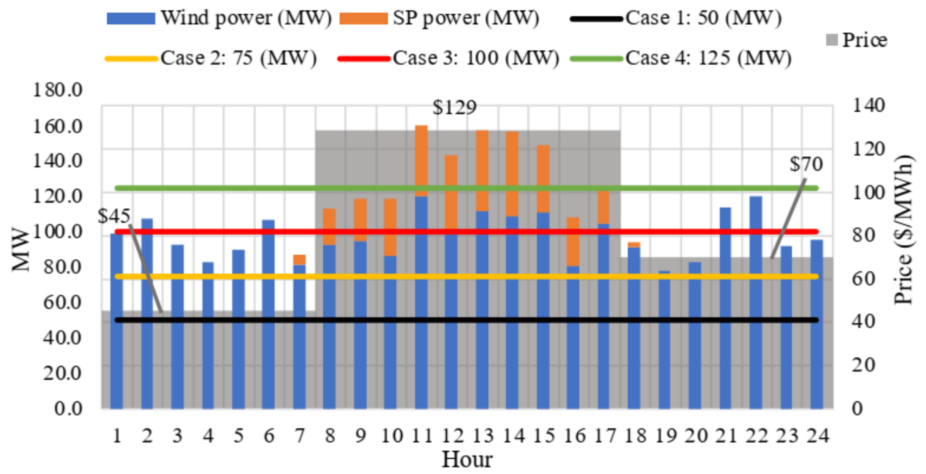


FIGURE 6. Generation of power plants and selection of rated powers for PSP.

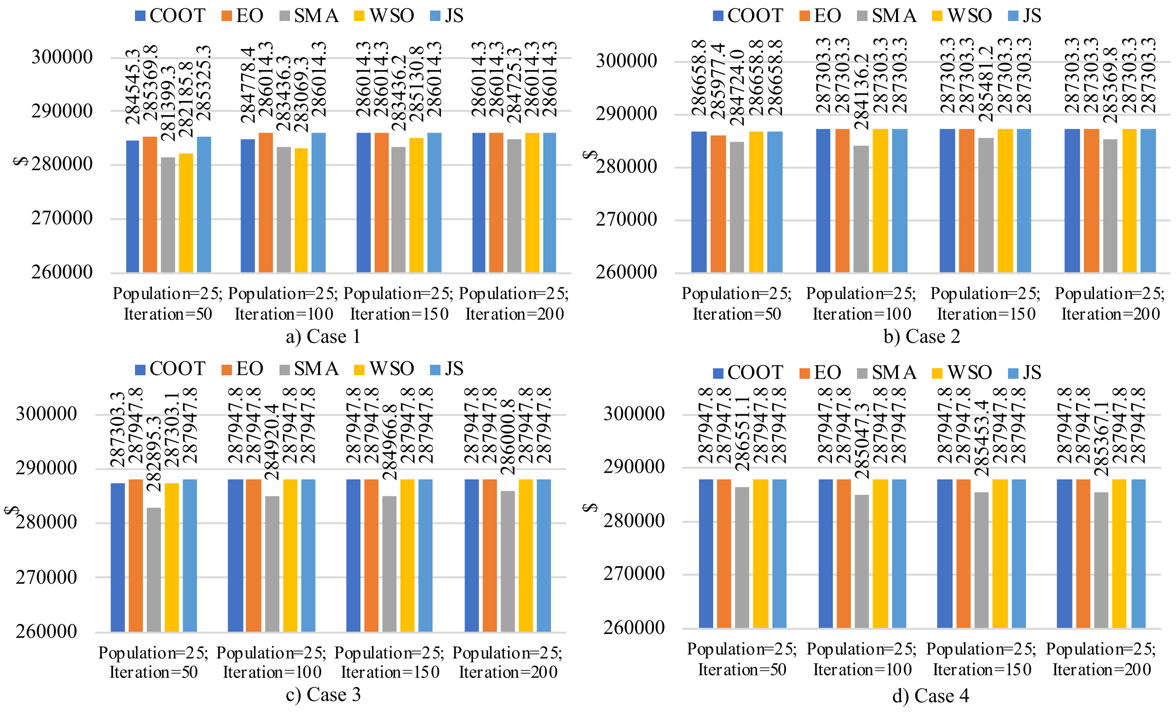


FIGURE 7. Total revenues obtained by five methods for four study cases of System 1 with different values of G_{max}.

Figure 7 shows that the highest total revenue values for Case 1, Case 2, Case 3, and Case 4 are $286,014.3, $287,303.3, $287,947.8, and $287,947.8. For each case, methods can find higher total revenue as the iteration number is increased, and they can reach the same highest total revenue when the iteration number is set to 150 and 200 for all cases, excluding SMA. However, some methods can reach the highest total revenue at a smaller iteration number due to the deviation of effectiveness. For Case 1, all methods cannot reach the highest total revenue of $286,014.3 when setting $G_{max} = 50$. But EO and JS can reach the highest total revenue for the setting of $G_{max} = 100$, whereas others fail. COOT together with EO and JS can reach the highest total revenue when G_{max} is increased to 150. Finally, WSO, together with COOT, EO, and JS, can reach the highest total revenue when G_{max} is increased to 200. For Case 1, JS and EO are the two strongest methods. Similarly, the highest revenue is reached earliest by the three methods EO, JS and COOT at $G_{max} =$

100 for Case 2, by EO and JS at $G_{max} = 50$ for Case 3, and by four methods WSO, EO, JS and COOT at $G_{max} = 50$ for Case 4.

Fifty total revenue values for Case 1 and Case 2 with $G_{max} = 100$, and for Case 3 and Case 4 with $G_{max} = 50$ given by five applied methods are sorted in descending order and plotted in Figure 8. The first point of each method in Case 1 in Figure 8 can be seen in Case 1 in Figure 7 with the setting of "Population=25 and Iteration=100". Observing Case 1 in Figure 7, EO and JS have the same value of \$286,014.3, but COOT, SMA and WSO reached smaller values than \$286,014.3. Those of these algorithms are \$284778.4, \$283436.3, \$283069.3. So, in Case 1 in Figure 8, EO and JS have the same first point, which is above the first point of COOT, SMA and WSO. Similarly, the first point of EO and JS is the same as others or greater than that of others for Case 2, Case 3, and Case 4 in Figure 8. The overview from the four cases can see JS and EO outperform the three remaining others, and a specific view can see that EO is more stable than JS for Case 1 and Case 3.

On the other hand, the four values of total revenue indicate that by increasing the rated power, the total revenue can be reached more, and the highest revenue can be reached at the rated power of 100 and 125 MW. Compared to Case 1 and Case 2, with the rated power of 50 and 75 MW, the highest revenue is greater than that of Case 1 and Case 2 by \$1,933.5 and \$644.5, corresponding to 0.68% and 0.22%. In summary, System 1 can reach the highest total revenue of \$287,947.8 when the rated power of CHEP is 100 and 125 MW. In addition, EO is the most robust method for all study cases.

C. OBTAINED RESULT FOR SYSTEM 2

This section shows the results for system 2 and investigates the most effective rated power of PSP for reaching the highest total revenue for the system. Because System 2 is more complicated than System 1, the five applied methods are implemented by setting a higher iteration number and population. Each method is run 200 times for each rated power case to find 200 optimal solutions in which every 50 trials have the same set of the iteration number and population. Namely, the four settings are arranged from the smallest to the highest values as follows: $S_{size} = 25$ and $G_{max} = 200$; $S_{size} = 25$ and $G_{max} = 500$; $S_{size} = 50$ and $G_{max} = 500$; and $S_{size} = 50$ and $G_{max} = 1,000$.

The overview through the results from four cases with different G_{max} values in Figure 9 shows that the highest total revenue equals \$303775.8 for Case 1, \$319585.8 for Case 2, \$305600.2 for Case 3 and \$287947.8 for Case 4. Clearly, Case 2 is the most effective since it reaches greater total revenue than Case 1 by \$15,810, Case 3 by \$13,985.6, and Case 4 by \$31,638. The greater money is equal to 5.2%, 4.58%, and 10.99% of revenue from Case 1, Case 3, and Case 4. So, the most effective rated power of PSP in System 2 is 75 MW.

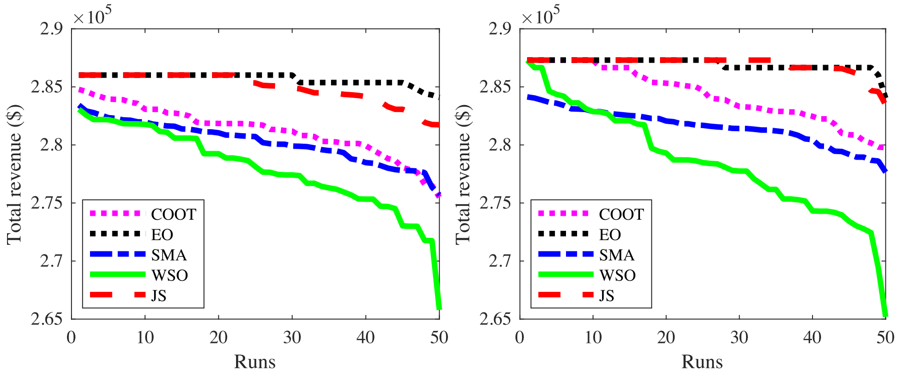
For Case 1, only EO finds the best total revenue of \$303775.8 with the settings: $S_{size} = 50$ and $G_{max} = 500$, and $S_{size} = 50$ and $G_{max} = 1,000$. Others cannot find the same revenue excluding COOT with the total revenue of \$303775.7 but only COOT reach the revenue with the setting of $S_{size} = 50$ and $G_{max} = 1,000$. For Case 2, EO can find the best total revenue with the second setting ($S_{size} = 25$ and $G_{max} = 500$) and other settings with higher population and iteration number. Meanwhile only COOT can find the same best total revenue with the third setting and the fourth setting. For Case 3, only EO and COOT can find the same best total revenue for four settings, whereas SMA and JS just find the revenue from the second to the fourth settings. Case 4 seems to be the simplest since all methods can reach the same best revenue for four settings, excluding SMA with smaller revenue than four others. To identify the performance of methods, fifty runs for each case with the smallest setting where the best total revenue was found are plotted in Figure 10. EO is the most stable algorithm for Cases 1, 3, and 4, excluding Case 2, worse than SMA and JS. However, this shortcoming has little influence on the performance evaluation of EO. So, EO is still the best method.

In summary, System 2 can reach the highest total revenue when PSP has a rated power of 75 MW, and EO is the most effective method among the five applied methods.

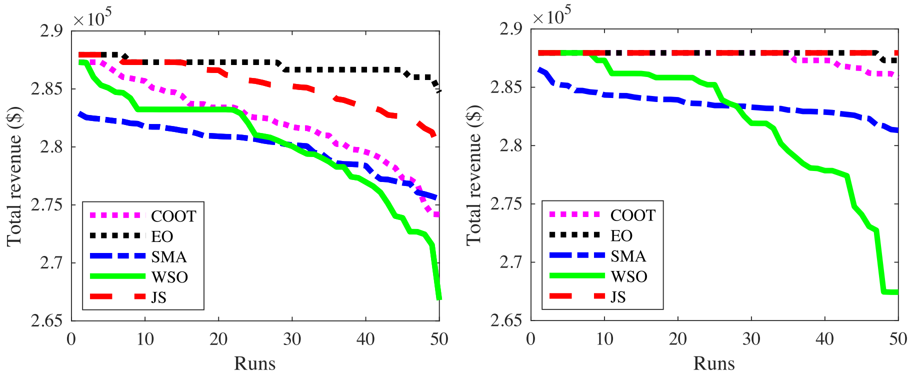
D. COMPARISON OF TOTAL REVENUES OBTAINED FOR TWO SYSTEMS

Figure 11 summarizes the results from four study cases that System 1 and System 2 obtained. Blue bars present the total revenue values of System 1, and yellow bars present the total revenue values of System 2. For each study case, the total revenue values from the two systems are compared to each other. The yellow bars are higher than the blue bars for Case 1, Case 2, and Case 3, but the height of the two bars is the same for Case 4. System 2 can reach higher total revenue than System 1 thanks to the water storage function by \$17,761.5 for Case 1, \$32,282.5 for Case 2, and \$17,652.4 for Case 3. The better total revenue values are equivalent to 6.21%, 11.24% and, 6.13% of the total revenue of System 1 for Case 1, Case 2, and Case 3, respectively.

System 1 has the highest total revenue of \$287,947.8 in Case 3 and Case 4, whereas System 2 has the highest total revenue of \$319,585.8 in Case 2. An exact calculation shows that System 2 can reach higher total revenue than System 1 by \$31,638, about 10.99% from System 1. System 1 should build a conventional hydropower plant with a rated 100 MW or 125 MW power, but System 2 needs a 75-MW pumped-storage hydroelectric plant. The water storage function of PSP is beneficial in reaching total revenue; however, the results could be better for Case 4. The cause of unexpected results should be analyzed to solve low total revenue. We go back to Figure 6 above to find the cause of the unexpected results of Case 4. Case 4 with the green line is only below orange bars at hours 11-15, so PSP can run the pump just for hours 11-15. However, the highest electric price can be seen

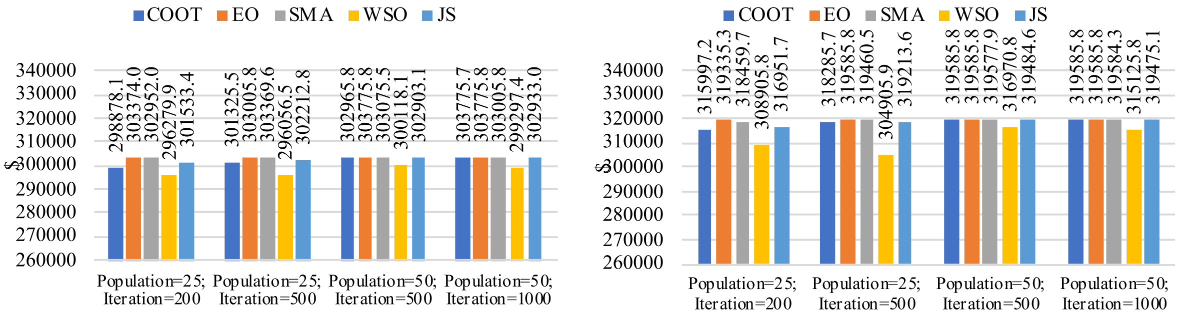


a) Case 1: $G_{max} = 100$ b) Case 2: $G_{max} = 100$

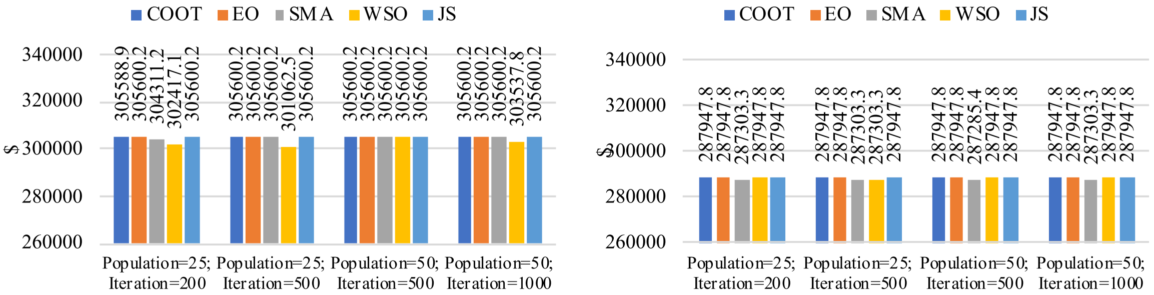


c) Case 3: $G_{max} = 50$ d) Case 4: $G_{max} = 50$

FIGURE 8. Revenue values of fifty runs obtained by five applied methods for four cases of System 1.



a) Case 1 b) Case 2

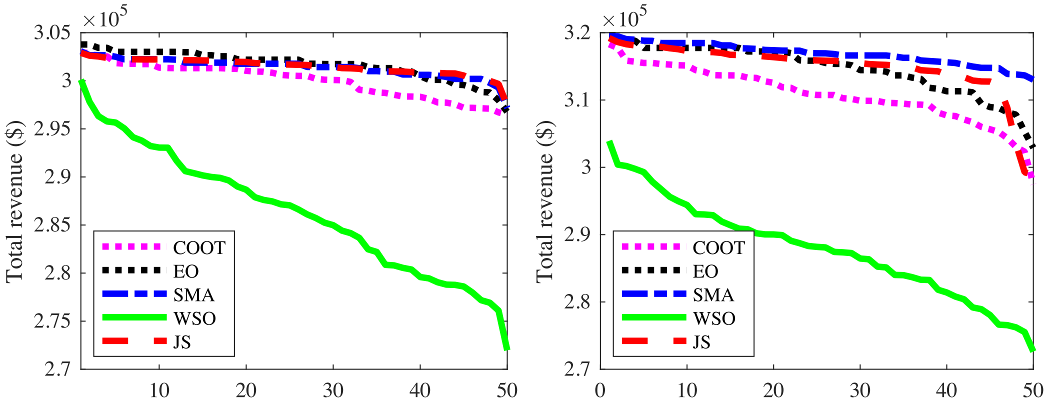


c) Case 3 d) Case 4

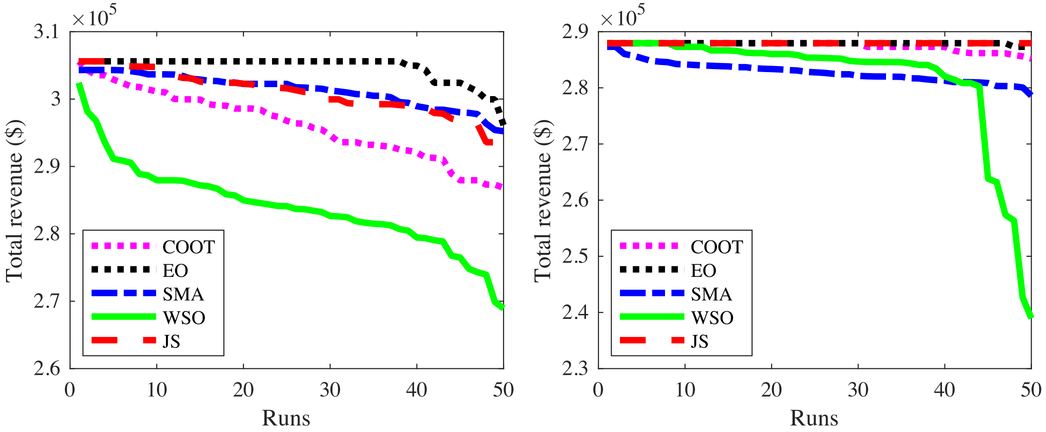
FIGURE 9. Total revenues obtained by five methods for four study cases of System 2 with different values of G_{max}.

at hours 8-17, but PSP can only implement water storage for hours 11-15. So, the PSP is unsuitable for reaching high total revenue if its rated power is 125 MW.

To clarify the reason that System 2 can reach higher total revenue than System 1 for Case 1, Case 2 and Case 3, and the same total revenue as System 1 for Case 4. Hourly revenue



a) Case 1($S_{size} = 50$ and $G_{max} = 500$) b) Case 2 ($S_{size} = 25$ and $G_{max} = 500$)



c) Case 3 ($S_{size} = 25$ and $G_{max} = 200$) d) Case 4 ($S_{size} = 25$ and $G_{max} = 200$)

FIGURE 10. **Revenue values of fifty runs obtained by five applied methods for four cases of System 2.**

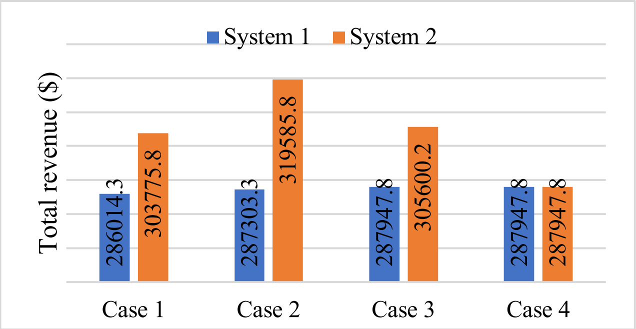


FIGURE 11. **Total revenue comparisons for four study cases from two applied systems.**

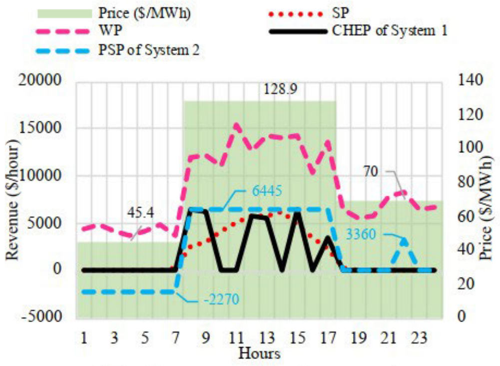
of CHEP in System 1 and PSP in System 2, together with the hourly revenue of the two systems, are plotted in Figure 12, Figure 13, Figure 14 and Figure 15 for Case 1, Case 2, Case 3 and Case 4, respectively. Figures a present hourly revenue of wind and solar power plant for the two systems, hourly revenue of CHEP of System 1 and hourly revenue of PSP of System 2. Each system has one SP and one WP with the same generation, so the two systems have the same hourly revenue for SP and WP. However, the hourly revenue of CHEP is for system 1 but the hourly revenue of PSP is for System 2. In addition, green areas, which were referred to the right vertical axis, were plotted to show the electric prices of twenty-four hours. The price is 45.4 \$/MWh for hours 1-7, 128.9 \$/MWh for hours 8-17, and 70 \$/MWh for hours 18-24. The revenue of SP at hours 7-18 reached the highest value of about \$6,000. The revenue of WP reached the highest value of about \$15,000 at hour 11. Figures b presents the total hourly revenue of each system and saving total hourly revenue of System 2 as compared to System 1. It denotes the savings total hourly revenue and is obtained by:

$$\Delta RE_h = RE_{S2,h} - RE_{S1,h} \tag{29}$$

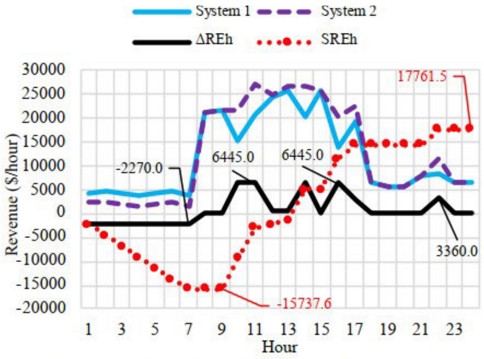
In addition, Figures b also present the sum of saving total hourly revenue from the first hour to the *hth* considered hour. The sum of saving cost is determined by:

$$SRE_h = \sum_{i=1}^{h} \Delta RE_i, \ with\ h = 1, \ldots, 24 \tag{30}$$

where SRE_h is the sum of saving total hourly revenue from the first hour to the *hth* hour; and ΔRE_i is the saving total

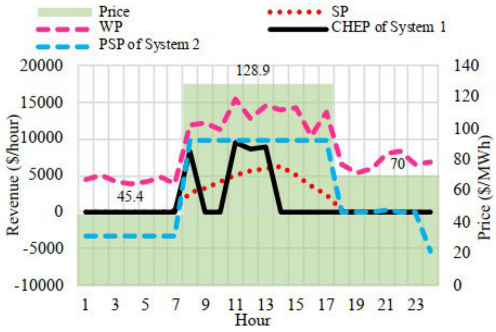


a) Hourly revenue of each power plant

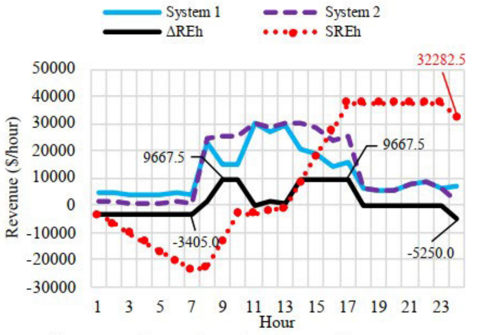


b) Comparison of total revenue of two systems

FIGURE 12. Summary of revenue obtained by two systems for Case 1.



a) Hourly revenue of each power plant

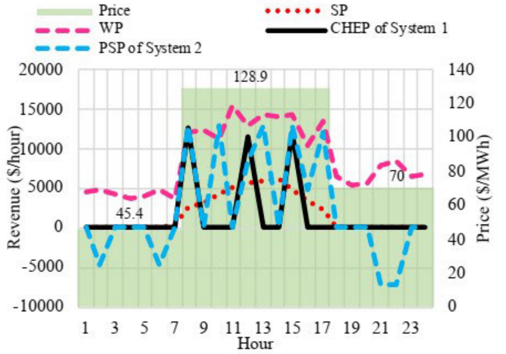


b) Comparison of total revenue of two systems

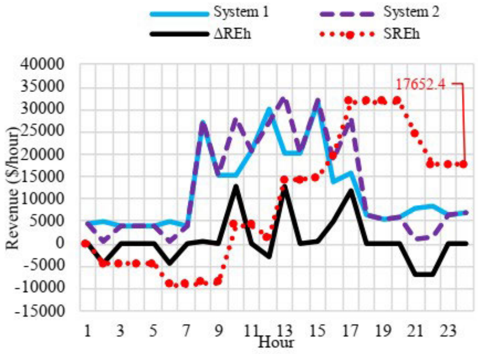
FIGURE 13. Summary of revenue obtained by two systems for Case 2.

hourly revenue of System 2 compared to System 1 at the *ith* hour. For the case $i = h = 1, \ldots, 24$, we have the following definition.

$$\Delta RE_i = \Delta RE_h \tag{31}$$

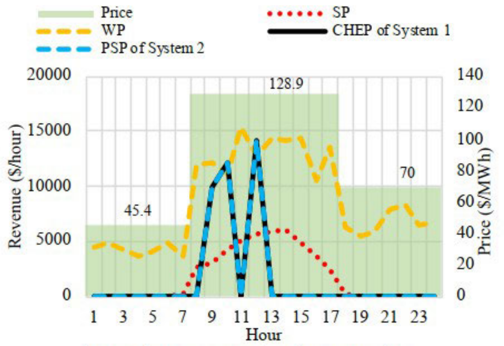


a) Hourly revenue of each power plant

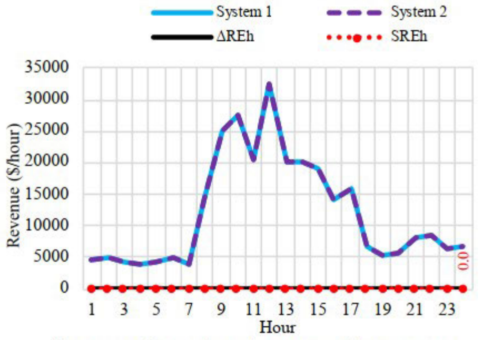


b) Comparison of total revenue of two systems

FIGURE 14. Summary of revenue obtained by two systems for Case 3.



a) Hourly revenue of each power plant



b) Comparison of total revenue of two systems

FIGURE 15. Summary of revenue obtained by two systems for Case 4.

From Equation (30), we can understand that SRE_h(with $h = 24$) is equal to saving total revenue of System 2 as compared to System 1. The saving money is obtained by:

$$Saving_{TRE} = \sum_{h=1}^{24} RE_{S2,h} - \sum_{h=1}^{24} RE_{S1,h} \tag{32}$$

where,

$$SRE_{h|h=24} = Saving_{TRE} \tag{33}$$

In Figure 12a, the revenue of CHEP in System 1 reached the highest revenue of $6,445 at hours 8-9. Similarly, the PSP in System 2 can reach the highest revenue of $6,445 at hours 8-17. PSP of System 2 suffers from minus revenue, – $2270 per hour, whereas CHEP of System 1 does not have revenue for hours 1-7 (the hours with the lowest price of $45.4 per MWh). For hours with a medium price of $70 per MWh, the two plants have approximately the same revenue, excluding hour 22, when PSP reaches a revenue of $3360, but CHEP has no money. On the contrary, the PSP of System 2 can reach the highest revenue of $6445 for ten hours with the highest price of $128.9 per MWh, but CHEP gets much lower revenue for the ten hours. Figure 12b compares the total hourly revenue obtained by the two systems. The black curve shows SRE_h in Eq. (29). The curve shows that System 1 can reach a higher benefit than System 2, just up to $2270, while System 2 can reach a higher revenue than System 1, up to $6,445. The red curve shows the values of SRE_h from the first hour to the last hour. The value drops during hours 1-7 with a low price, and the lowest value is -$15737.6. The value increases gradually or decreases slightly from hour 8 to the last hour. Finally, it reached the last venue of $17,761.5 at the last hour, and it is also the saving revenue that System 2 was more effective than System 1.

Figure 13 and Figure 14 also have the same manner as Figure 12. It is noted that Case 2 in Figure 13 is the most rated power of PSP, so the red curve in Figure 13 tends to increase highly from hour 8 to the last hour. On the contrary, Figure 15 differs from Figure 12, Figure 13, and Figure 14. The revenue of CHEP and PSP are the same, leading to the same hourly revenue between the two systems.

Optimal power outputs of CHEP of System 1 and PSP of System 2 for four cases are plotted in Figure 16, Figure 17, Figure 18, and Figure 19. Table 2 summarizes the generation operation conditions of CHEP and PSP, and the pump operation conditions of PSP for four cases. The view from the four figures shows that CHEP and PSP focus on generation for hours with high prices from hour 8 to hour 17. In Case 1 and Case 2, PSP operated the pump over the first seven hours with the lowest price to save water and generated electricity over 10 hours (hours 8-17) with the highest electricity. CHEP also generates electricity at hours 8, 9, 12, 13, 15, and 18 because it does not have enough water to produce electricity for the ten high-price hours.

To clarify the impact of the pump power and generation on the total revenue, Table 3 is established to show energy accumulated energy of the PSP at the end of each hour. The pump power and generation of the PSP in Figures 16-19 are accumulated at the end of each hour. The PSP has run the pump with the power of (–50 MW) for the first seven hours as shown in Figure 16, so the accumulated energy at the end of each hour decreased gradually, −50 MWh at the end of hour 1, and reaching -350 MWh at the end of hour 7. The value of −350 MWh means the PSP has used the energy of 350 MWh to run the pump from hour 1 to hour 7. Then, the PSP discharged water to produce electricity from hour 8 to hour 17, corresponding to the increase of the accumulated energy from −300 MWh to 150 MWh. It means that the PSP has compensated for the used energy of 350 MWh and produced an energy of 150 MWh. From hour 18 to hour 24, the PSP only discharged water to produce 38 MW at hour

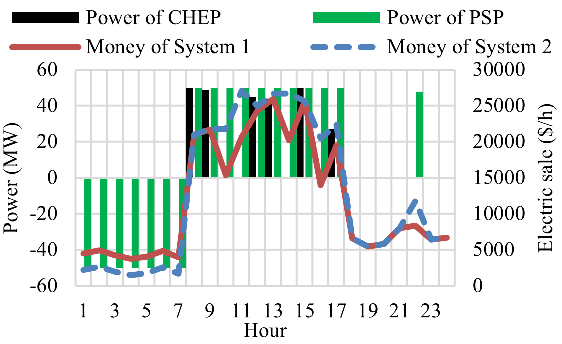


FIGURE 16. Power output of CHEP and PSP, and electric sale revnue at each hour of two systems for Case 1.

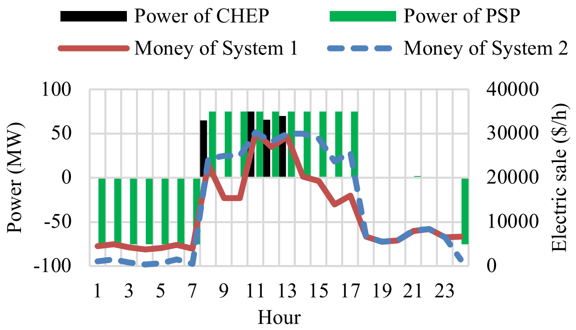


FIGURE 17. Power output of CHEP and PSP, and electric sale revnue at each hour of two systems for Case 2.

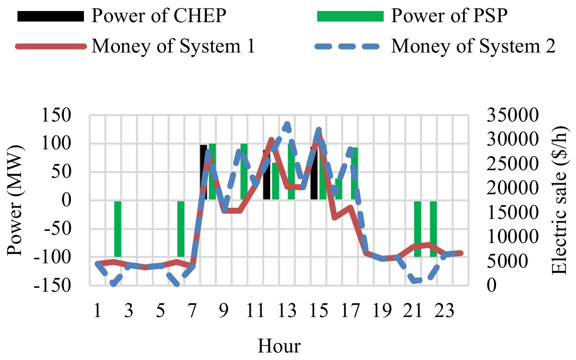


FIGURE 18. Power output of CHEP and PSP, and electric sale revnue at each hour of two systems for Case 3.

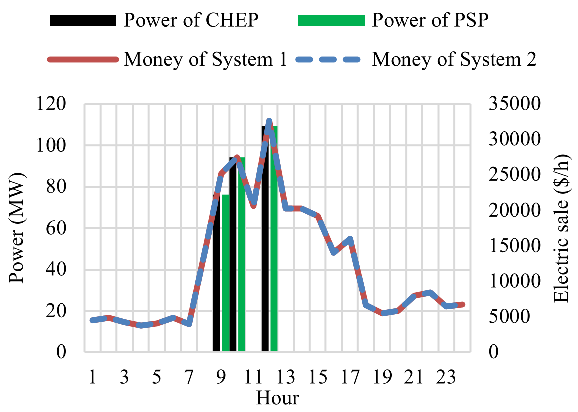


FIGURE 19. Power output of CHEP and PSP, and electric sale revnue at each hour of two systems for Case 4.

22, so the accumulated energy at the end of hour 22 to hour 24 was the same and equal to 198 MWh. Observing Figure 17, the 75-MW PSP has the same operation as the 50-MW PSP for hours 1-17. It used an energy of 525 MWh for hours 1-7, and then it produced electricity to compensate for the used energy and produced an energy of 225 MWh at the end of hour 17. The PSP produced 2 MW at hour 21, but it run the pump at hour 24. So, the 75-MW PSP has reached the energy of 152 MWh for one operation day. With the same analysis, the 100-MW PSP, shown in Figure 18, has produced an energy of 196 MWh for one operation day. The 125-MW PSP, shown in Figure 19, has not run pumped over one operation day, and it could reach the highest energy of 280 MWh among four cases. However, as indicated in Figure 11, Hybrid system 2 with the 125-MW PSP, reached the lowest total revenue, whereas the 75-MW PSP supported Hybrid system 2 to reach the highest total revenue. So, it can lead to a conclusion that the 125-MW PSP was beneficial for the system needing the highest energy, whereas the 75-MW PSP was essential for reaching the highest total revenue.

TABLE 2. Summary of information for CHEP in System 1 and PSP in System 2.

Case	Pump power (MW)	Maximum possible power output of CHPE and PSP (MW)	Possible hours for running pump of PSP
1	50	50	All hours (**8-17**)*
2	75	75	All hours (**8-17**)*
3	100	100	2, 6, **8-17***, 20 and 21
4	125	125	**10-15***

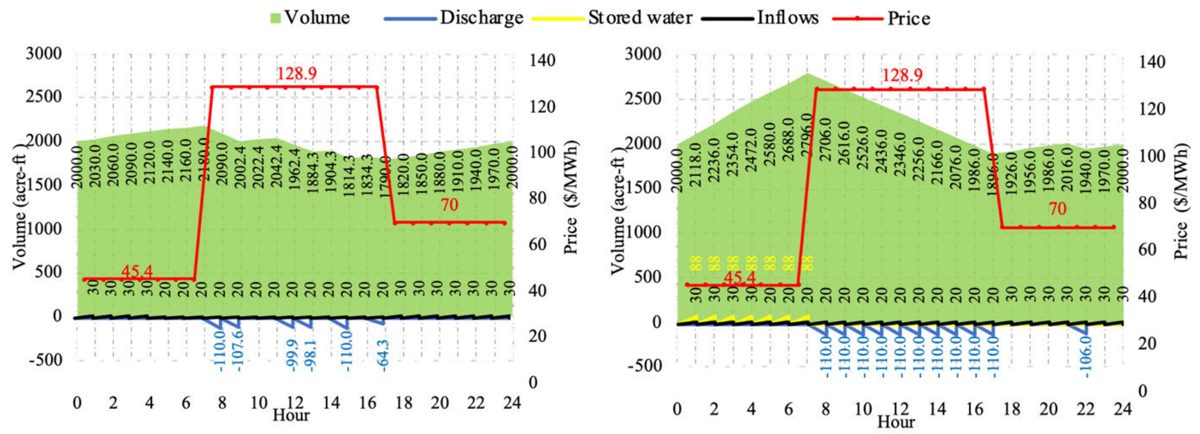
*Numbers in bold means hours with high prices

Figure 20, Figure 21, Figure 22 and Figure 23 are depicted to show the optimal operation scheduling of CHEP in System 1 and PSP in System 2 for four study cases. In the figures, the areas in green are the volume of the reservoir with the same initial and endpoints, which are 2000 acre-ft. From Case 1 to Case 3, the reservoir of the two plants reaches the peak volume at the end of hour 7, and there are no discharges for the first seven hours. The peak volume of PSP is much higher than CHEP's for the first three cases. The peak volumes of PSP are, respectively, 2796, 3076 and 2516 acre-ft, but those of the CHEP are the same for three cases and equal to 2180 acre-ft. The two plants have the same strategy of saving water for the first seven hours, but PSP can save more water thanks to the pump function. Table 1 indicated that PSP could store 88, 128, 168 and 208 arce-ft/hour in Case 1, Case 2, Case 3, and Case 4, respectively. And the corresponding values can be seen in Figure 20b, Figure 21b, and Figure 22b, but they cannot be seen in Figure 23b. Figure 6 indicates that PSP can store water for every hour in Case 1 and Case 2, and hours 1-7 have the lowest electricity price. So, Case 1 and Case 2 have the same feature: water is stored from hour 1 to hour 7, and the water level constantly increases to the peak. We can see values of 88 and 128 in yellow in Figure 20b and Figure 21b. In addition, PSP has flushed water to produce electricity for hours 8-17 to get the maximum revenue because the price is the highest over these hours. We can see values -110 in Figure 20b and -160 in Figure 21b. CHEP also flushed water over these hours, but total inflows are not high to save water for flushing. In summary, the effectiveness of System 2 in reaching greater total revenue than System 1 is derived from the water storage at low electricity price hours and full power generation at high electricity price hours that PSP can implement. CHEP is limited in its advantages, leading to the ineffectiveness of System 1.

TABLE 3. Accumulated energy (MWh) of the PSP with different rated generation.

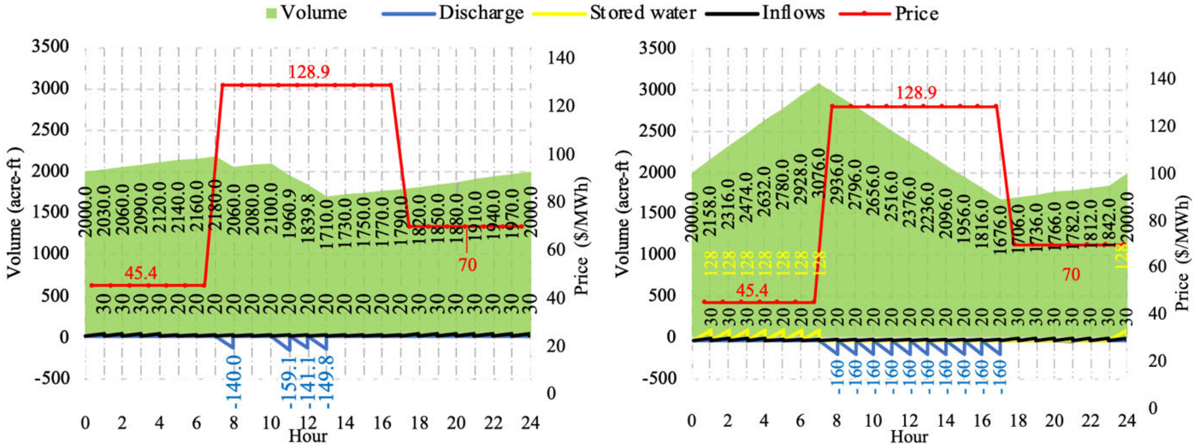
	Rated generation of PSP (MW)			
Hour	50	75	100	125
1	-50	-75	0	0
2	-100	-150	-100	0
3	-150	-225	-100	0
4	-200	-300	-100	0
5	-250	-375	-100	0
6	-300	-450	-200	0
7	-350	-525	-200	0
8	-300	-450	-100	0
9	-250	-375	-100	76.28
10	-200	-300	0	170.45
11	-150	-225	0	170.45
12	-100	-150	65.86	280
13	-50	-75	165.86	280
14	0	0	165.86	280
15	50	75	264.91	280
16	100	150	303.05	280
17	150	225	396	280
18	150	225	396	280
19	150	225	396	280
20	150	225	396	280
21	150	227	296	280
22	198	227	196	280
23	198	227	196	280
24	198	152	196	280

Figure 6 shows that Case 3 and especially Case 4 are restricted for performing water storage. It can be performed for Case 3 at hours 2, 6, 8-17, 20, and 21, and for Case 4 at hours 10-15. On the other hand, the electricity price is the



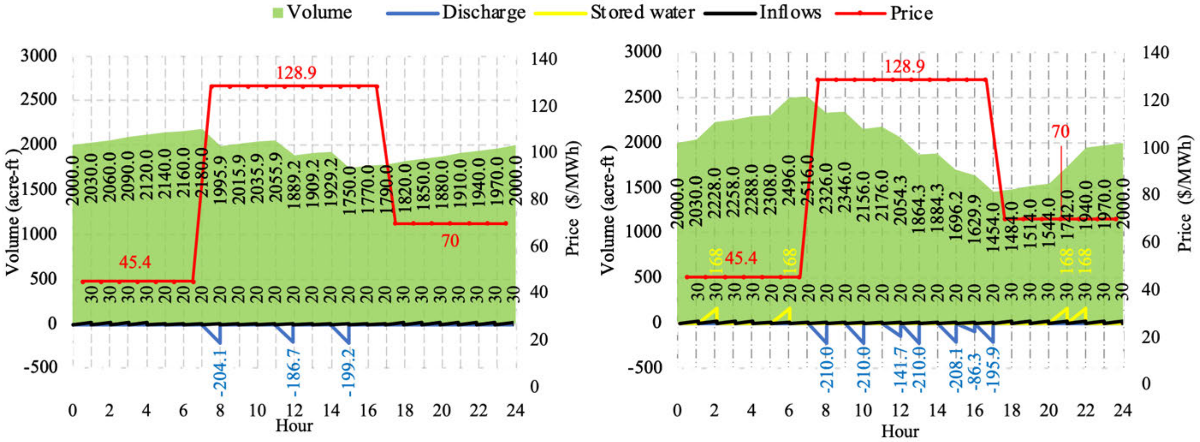
a) Case 1 system 1 b) Case 1 system 2

FIGURE 20. Optimal operation scheduling of CHEP in System 1 and PSP in System 2 for Case 1.



a) Case 2 system 1 b) Case 2 system 2

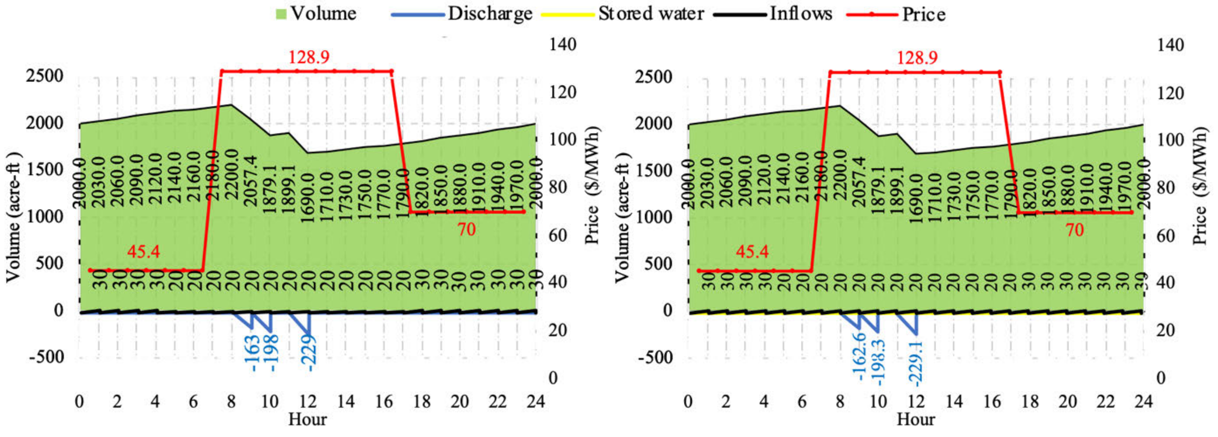
FIGURE 21. Optimal operation scheduling of CHEP in System 1 and PSP in System 2 for Case 2.



a) Case 3 system 1 b) Case 3 system 2

FIGURE 22. Optimal operation scheduling of CHEP in System 1 and PSP in System 2 for Case 3.

highest for hours 8-17, and medium for hours 18-24. Therefore, PSP has selected hours 2 and 6 with the lowest price and hours 20 and 21 with the medium price to save water. This information can be seen in Figure 22b for Case 3. PSP can run a pump to save water in Case 4 over hours 10-15, but these hours have the highest electricity price. As a result, PSP did not run the pump for the high-price hours, and PSP acted as a conventional plant. This is the reason why System



a) Case 4 system 1

b) Case 4 system 2

FIGURE 23. Optimal operation scheduling of CHEP in System 1 and PSP in System 2 for Case 4.

TABLE 4. Coefficients of discharge function of CHEP in System 1 and PSP in System 2.

m	γ_3	γ_2	γ_1	$RVolume_{Max}$ (acre-ft)	$RVolume_{Min}$ (acre-ft)	$RVolume_{End}$ (acre-ft)	$RVolume_{Initial}$ (acre-ft)
1	10	2	0	4,000	1,000	2,000	2,000

TABLE 5. Inflows to upper reservoirs of CHEP in System 1 and PSP in System 2.

Hour	Inflow (acre-ft)	Hour	Inflow (acre-ft)	Hour	Inflow (acre-ft)
1-4	30	5-17	20	18-24	30

2 has the same total revenue as System 1 for Case 4, and PSP has the same optimal operation scheduling as CHEP. We can compare Figure 23a and Figure 23b to identify the similarity. The disadvantages of PSP in Case 4 indicated that the determination of rated power for PSP should be carefully calculated. As rated power is selected to be high, using energy with high electricity prices for storage water is impossible, and PSP just works as a CHEP.

V. CONCLUSION

This paper applied SMA, EO, JS, COOT and WSO to reach the maximum total electricity sale revenue for two hybrid systems for one day. The two hybrid systems have the same wind power plant and the same solar photovoltaic power plant but different types of hydroelectric power plants, CHEP in the first one and PSP in the second one. The PSP and CHEP had the same generation characteristics, such as discharge limit, generation limit, and discharge-generation function. The maximum total electricity sale revenue of the two system was determined for four rated generation values of CHEP and PSP, including 50, 75, 100, and 125 MW. The results and the conclusions can be summarized as follows:

1. The total revenues were \$286,014.3, \$287,303.3, \$287,947.8, and \$287,947.8 for Hybrid system 1, and \$303,775.8, \$319,585.8, \$305,600.2 and \$287,947.8 for Hybrid system 2. Hybrid system 2 could reach a greater total revenue than Hybrid system 1 by 6.21%, 11.24%, and 6.13% when the rated generation of PSP and CHEP was 50, 75, and 100 MW, respectively. Hybrid system 2 got higher revenue than Hybrid system 1 by \$31,638, about 10.99%. The best-rated generation was 100 MW for the CHEP and 75 MW for the PSP. Clearly, the PSP with a lower capacity can reach a greater benefit than the CHEP. So, the construction of the PSPs is more essential for the power systems than the CHEPs. However, determining the most suitable capacity of the PSP must be carefully calculated.
2. For one operation day with the rated generation of 50, 75, and 100 MW, the PSP has used 350, 600, and 400 MWh to pump water back to the upper reservoir and produced 548, 752, and 596 MWh, respectively. The benefit that the power plant could reach was 198, 152, and 196 MWh. However, the CHEP produced 265, 275, and 280 MWh for the cases. Clearly, CHEP could reach a greater energy than the PSP for one operating day, but CHEP's total revenue was much smaller than the
3. PSP's. For one operation day with a rated generation of 125 MW, the PSP and CHEP had the same solution. The PSP only produced electricity as the CHEP, and it did not pump water back to the upper reservoir. They had the

same produced energy of 280 MWh. The results indicated that the CHEP could reach higher energy than PSP, but its revenue was not as high as the PSP's. So, power systems should use CHEPs to maximize obtained energy, but they should use PSPs to maximize electricity sales revenue.

4. The PSP pumped water at low electric price hours and generated full power at other high electric price hours. So, the optimization operation of the PSP depends on the inflows to upper reservoirs and hourly electricity prices.
5. EO was the best optimization tool among the five applied ones. It could reach the same or greater total revenue than SMA, JS, COOT, and WSO, although all the algorithms were set to the same iteration number.

The high achievements of the PSP and useful indications for power systems above are significant contributions of the study. However, the study could not consider data and more constraints in real power systems, such as wind speed, solar radiation, national electric markets, transmission power networks, and so on. The upcoming studies will have higher quality contributions if the limitations can be improved.

APPENDIX

See Tables 4 and 5.

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