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Optimization model of the Joint operation of Pumped-Storage Hydro Plant and Wind Farm: Considering the Imbalances of Wind Power Output

***Abstract**. Since the future energy production of wind farm is uneasy to be precisely predicted, the integration of wind power into electric power system has been a difficult problem for many years. Recently, the widely emerged pumped-storage hydro plant can be used to balance the unstable output of wind farm, because the pumped-storage hydro plant can adjust its production to compensate wind power prediction errors. In this paper, a joint operation model between the wind farm and pumped-storage hydro plant is proposed. In this mode, there are two targets for the system: 1) maximizing the daily revenue of pumped-storage hydro plant; 2) partially compensating the deviations resulted from wind power output imbalances. Then we analyzed the economic benefits of pumped-storage hydro plant in the condition of both independent operation and joint operation. Finally, the model is applied in the actual operation of pumped-storage hydro plant. From the case study we can see that power incomes of pumped-storage hydro plant alone is reduced under joint operation model, while the comprehensive economic effect has actually increased in response to the stable output of wind power.*

***Streszczenie.** W artykule przedstawiono model współpracy farmy wiatrowej z elektrownią szczytowo-pompową. Wspólna praca tych jednostek wynika z niestabilności energii wiatrowej i pozwala na jej redukcję. Zbudowany model umożliwia realizację dwóch celów: maksymalizacji dziennego zysku z magazynowania energii w elektrowni oraz częściowe ograniczenie wahań wytwarzanej energii, wynikające z niestabilności wiatru. Dokonano także analizy ekonomicznej zysków z pracy jednostek w trybach współpracy oraz pracy niezależnej. Przeprowadzono weryfikację opracowanego modelu na rzeczywistych danych. (**Model optymalizacji współpracy elektrowni szczytowo-pompowej i farmy wiatrowej – zjawisko niestabilności mocy wyjściowej elektrowni wiatrowej**).*

Keywords: joint operation model, integration of wind power, pumped-storage hydro plant.
Słowa kluczowe: model pracy wspólnej, integracja energii wiatrowej, elektrownia szczytowo-pompowa.

Introduction

Over the decades, as wind power worldwide has accelerated its space in integrating into the power grid, an increasing concern is focusing on the impact of large-scale wind power integration into the power grid on the scheduling and operation of the network. Due to the intermittency, randomness and counter-peak regulation of wind power, some specific measures rather than those used for conventional generators should be adopted to dispatch, control and manage the wind turbines [1-6]. The key is that deviations between the predicted values and actual values of wind power output will give rise to imbalances between the actual wind power output and the electricity needed by power grid companies, causing negative impact on the wind power scheduling and power grid operation. Despite the research on the wind output prediction, power grid dispatching department still cannot accurately predict the variations of wind power output due to the inaccuracy in prediction techniques and insufficient experience.

Viewed as an important kind of storage units in the power system, the pumped-storage hydro plant has the functions of peak shaving, frequency modulation and phase modulation, which reduces the adverse impact of wind integration on the power grid and at the same time ensures the safe, reliable and economic operation of the power gird. A consensus that the large scale development of clean energy such as wind power should be coordinated with a suitable amount of pumped-storage hydro plants has been reached among relevant industries.

Currently, abundant investigations have discussed how to apply storage system to deal with the wind power integration into the power gird. Reference [7] talks about the joint operation between wind farm and traditional muti-reservior hydropower used to solve distribution congestion in adjacent lines. Reference [8] investigates the optimal capacity commitment between the wind farm and pumped-storage hydro plant to find the best way used to control the wind farm. Reference [9] proposes the optimization method for the joint operation between the wind power and pumped-storage hydro plant based on the day ahead load prediction and wind power output prediction, exploring the new mode to compensate wind power output. Reference [10] establishes a bi-level optimization model to determine the overall optimal economic benefits of wind power and pumped-storage hydro plant in electricity market environment. Reference [11] sets the economic benefits of wind farm as the target, and demonstrates the validity of joint operation between wind farm and pumped-storage hydro plant through case studies. Reference [12] establishes the quantitative evaluation model for the wind power and pumped-storage hydro plant system and energy conversion efficiency in the consideration of peak and valley prices, highlightening the peak load shifting effect of pumped-storage hydro plant. Reference [13] suggests two ways to reduce the losses from the imbalances of the wind power output. One is to motivate wind farms to participate in day ahead electricity market based on predicted wind power output values to reduce risks. The other is to enable the joint operation between wind farm and pumped-storage hydro plant to minimize the losses.

References mentioned above mainly focus on the storage function of pumped-storage hydro plant in the wind farms, and rarely discuss how to utilize pumped-storage hydro plant to compensate the deviations of wind power output. In addition, optimization models established mainly center on the economic benefits of wind-pumped-storage hydro plant system, and the impact of the joint operation on pumped-storage hydro plant is insufficiently described. In this paper, an optimization model is established to maximize the economic benefits of pumped-storage hydro plant, exploring the optimal operation mode of pumped-storage hydro plant. Then, based on the independent operation of pumped-storage hydro plant, the joint operation between wind farm and pumped-storage hydro plant is proposed to investigate the optimal operation mode of pumped-storage hydro plant and impact of joint operation on the economic benefits of pumped-storage hydro plant. Finally, the technical and economic feasibility of joint operation between wind farm and economic benefits of pumped-storage hydro plant is demonstrated by case studies.

Problem Formulation

Over the decades, as wind power worldwide has accelerated its space in integrating into the power grid, an increasing concern is focusing on the impact of large-scale wind power integration into the power grid on the scheduling and operation of pumped-storage hydro plant.

Before we analyze the joint operation problem, we firstly introduce the independent operation of pumped-storage hydro plant. The operation mode of pumped-storage hydro plant should be clarified. Some assumptions are made as follows.

(1) Daily operation of pumped-storage hydro plant. A day is classified into 24 time intervals to apply real time data discretization.

(2) Electricity regulation is cancelled in market environment, and accurate prediction on electricity price of the following day is achieved.

(3) The pumped-storage hydro plant pumps water in valley load time and generates electricity during peak load time.

The optimization model is aimed at maximizing the daily revenues of pumped-storage hydro plant, as the following (1)-(8) indicate.

(1) $$\max \sum_{i=1}^{24} (c_i \overline{P}_{Hi} - c_{Pi} \overline{P}_{Pi})$$

(2) $$E_{i+1} = E_i + i(\eta_P \overline{P}_{Pi} - \frac{\overline{P}_{Hi}}{\eta_H})$$

(3) $$E_1 = E_1^{\exp}$$

(4) $$E_{n+1} = E_{n+1}^{\exp}$$

(5) $$0 \le \overline{P}_{Hi} \le P_H^u$$

(6) $$\overline{P}_{Hi} \le \eta_H \frac{E_i}{i}$$

(7) $$0 \le \overline{P}_{Pi} \le P_P^u$$

(8) $$0 \le E_i \le E^u$$

$$\forall i = 1,2,3,\cdots,24$$

where, c_i is the electricity price at hour i; c_{Pi} is the operation costs per MW at hour i (including electricity purchasing costs); $\overline{P}_{Hi}$ is the units capacity at generating mode at hour i ; $\overline{P}_{Pi}$ is the units capacity at pumping mode at hour i ; E_i is the energy storage of upper reservoirs; η_P is the overall efficiency at pumping mode; η_H is the overall efficiency at generating mode; P_H^u is the upper limits of capacity at generating mode; P_P^u is the upper limits of capacity at pumping mode; E^u is the upper limits of energy storage capacity of upper reservoirs.

Equation (1) shows the difference between generating revenues and pumping costs which include electricity costs and operation costs. In (2), the energy storage level of the upper reservoir in the following hour can be obtained, which is associated with the operation capacity and efficiency of different operating mode. Generally, the initial and final values of energy storage level of the upper and lower reservoirs is assumed to be the same and be known to us, as is shown in (3) and (4). Constraints like unit capacity and energy storage capacity of reservoirs are given in (5)-(8).

In the joint operation model of pumped-storage hydro plant and wind farm, some assumptions about the wind farm operation and the joint operation mode are presented as follows.

(1) The wind farm runs the responsibility of predicting the wind power output in the following day and then sends the predicted values to the dispatching department who is responsible for arranging the wind power integration into the grid.

(2) When the deviations between the predicted value and actual value of wind power output exceed a certain value, some economic punishment should be carried out on the wind farm. Generally, the wind farm need purchase some reserve capacity in ancillary service market to compensate the deviations.

(3) When the joint operation mode of pumped-storage hydro plant and wind farm is adopted, the wind farm can sign electricity contract with pumped-storage hydro plant in order to compensate the deviations.

In the joint operation mode, there are two targets for pumped-storage hydro plant: 1) maximizing the daily revenue of pumped-storage hydro plant; 2) partially compensating the deviations resulted from wind power output imbalances. Therefore, the pumped-storage hydro plant has to adjust its operation mode to coordinate with the wind power. The joint operation model of the pumped-storage hydro plant and wind farm is shown as follows.

(9) $$\max \sum_{i=1}^{24} (c_i \overline{P}_{Hi} - c_{Pi} \overline{P}_{Pi})$$

(10) $$E_{i+1} = E_i + i(\eta_P \overline{P}_{Pi} - \frac{\overline{P}_{Hi}}{\eta_H})$$

(11) $$E_1 = E_1^{\exp}$$

(12) $$E_{n+1} = E_{n+1}^{\exp}$$

(13) $$0 \le \overline{P}_{Hi} \le (P_H^u - P_{Wi}^m)$$

(14) $$\overline{P}_{Hi} \le \eta_H \frac{E_i}{i}$$

(15) $$0 \le \overline{P}_{Pi} \le (P_P^u - P_{Wi}^M)$$

(16) $$E_i^S \le E_i \le (E^u - E_i^R)$$

$$\forall i = 1,2,3,\cdots,24$$

where, P_{Wi}^m is the maximum negative blance wind power output; P_{Wi}^M is the maximum positive blance wind power output; E_i^S is minimum energy storage for the upper reservoir; E_i^R is the reserved wind power storage capacity for the upper reservoir.

It can be seen that (9)-(12) and (14) are identical to those in Section 2.1. The different equations such as (13), (15) and (16) show the constraints like unit capacity and energy storage capacity of reservoirs.

At the pumping mode, when the actual wind power output is lower than the predicted one, the pumped-storage hydro plant should pump less so that the deviations can be mitigated. On the contrary, when the actual wind power output exceeds the predicted one, the pumped-storage hydro plant should pump more to store the extra wind power. Therefore, the upper limits of pumping output for the pumped-storage hydro plant during each time interval is $P_P^u - P_{Wi}^M$, as is given in (15).

At generating mode, when the actual wind power output is lower than the predicted one, it is necessary to increase the generation capacity. That is to say, the pumped-storage hydro plant should provide some reserve capacity to compensate wind power output shortage. Therefore, the upper limits of the pumped-storage hydro plant output during each time interval is $P_H^u - P_{Wi}^m$, as is shown in (13). Conversely, when the actual wind power output exceeds the predicted one, the pumped-storage hydro plant should reduce its output to balance the extra wind power output.

Because the pumped-storage hydro plant is used to compensate the deviations from wind power output, the upper reservoir should keep the reserved storage capacity and at the same time remain the minimum storage capacity, as is shown in (16). Note that both E_1^{esp} and E_{n+1}^{esp} should exceed the minimum storage capacity.

Based on that discuss, the revenue model of joint operation is given in the next part.

Admittedly, the revenue model of joint operation should consider the electricity revenue, pumping costs, and costs or benefits in reserve capacity market resulted from the deviations between the actual and predicted output. The revenue model of joint operation is presented as follows.

(17) $$R = \sum_{i=1}^{24} (c_i \bar{P}_{WHPi} + d)$$

(18) $$d = \begin{cases} c_i^{sell}(P_{WHPi} - \bar{P}_{WHPi}); P_{WHPi} \geq \bar{P}_{WHPi} \\ c_i^{buy}(P_{WHPi} - \bar{P}_{WHPi}); P_{WHPi} \leq \bar{P}_{WHPi} \end{cases}$$

(19) $$\bar{P}_{WHPi} = \bar{P}_{Wi} + \bar{P}_{Hi} - \bar{P}_{Pi}$$

(20) $$P_{WHPi} = P_{Wi} + P_{Hi} - P_{Pi}$$

where, R is the revenue of joint operation; c_i^{sell} is the selling price of reserve capacity per MW; c_i^{buy} is purchasing price of reserve capacity per MW.

Factors that influence the revenue of joint operation include electricity price, energy costs, deviation costs and wind power output, among which the electricity price and actual wind power output are the decisive ones and are also seasonal. Therefore, compared with the revenue in summer, the revenue of joint operation in winter should be analyzed differently.

Case study

The independent operation model and joint operation model are applied in the actual operation of pumped-storage hydro plant respectively, exploring the optimal operation mode under these two cases[12]. It should be noted that electricity price is predicted values while the wind power output during each hour is coming from historic data. Hence, the calculation results obtained are predicted values. The initial data are presented as: P_H^u =32.8MW; P_P^u =40.3MW; E_u=240MWh; η_H=92%; η_P=92%; P_W^u =30MW; The corresponding per unit values are: P_P^u =1.34pu; E_u=8.00pu. It can be seen from Fig.1 that (a) and (b) respectively shows the optimal operation mode of the pumped-storage hydro plant under independent and joint operation. The vertical axis is described in the form of per unit value. Fig.1 indicates how the four parameters including P_P^u, P_H^u, E_u and c_i change over time. Particularly, electricity price c_i is the decisive factor and the optimal operation mode will vary with the electricity price.

In Fig.1 (a), the pumped-storage hydro plant operates independently. Initially, the pumped-storage hydro plant is in idle mode and the energy storage in the upper reservoir is E_1^{esp}. During the low electricity price time (2:00-7:00), the pumped-storage hydro plant operates in pumping mode until the upper reservoir reaches its optimal energy storage capacity. Then, the pumped-storage hydro plant remains in idle mode. During the high electricity price time (17:00-23:00), the pumped-storage hydro plant operates in generating mode and gains revenues by selling electricity to the grid until the upper reservoir reaches E_{n+1}^{esp}. The pumped-storage hydro plant keeps in idle mode after 23:00.

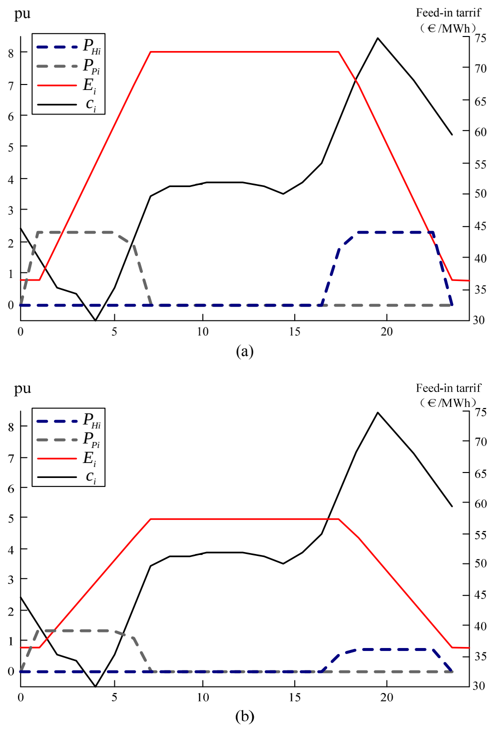

Fig.1. Optimal operation for hydro-pump plant under two operation mode

In Fig.1 (b), the pumped-storage hydro plant operates coordinately with the wind farm. Generally, the wind farm will sign an electricity contract with the pumped-storage hydro plant, saying that the pumped-storage hydro plant should compensate 90% of the deviations form wind power output. Thus, the pumped-storage hydro plant must provide sufficient reserve capacity. Compared with Fig.1 (a), the output of the pumped-storage hydro plant in Fig.1 (b) declines and the energy storage in the upper reservoir falls accordingly, which is resulted from the deviations of wind power output.

It is essential for the pumped-storage hydro plant to determine the percentage to compensate the deviations in joint operation. By calculation, if the percentage reaches 95%, the reserved capacity of the pumped-storage hydro plant to deal with extra wind power output will increase by 18% while the minimum energy storage of the upper reservoir in response to the wind power output shortage will rise by 26%, which imposes a negative impact on the operation of the pumped-storage hydro plant obviously.

The actual operation data are utilized to validate the effect of the pumped-storage hydro plant to compensate the deviations from wind power output[12]. The calculation results are obtained using Matlab. The comparison between actual operation and scheduling operation by the calculation results are described in Fig.2.

Fig.2. (a), it is clear that the actual energy storage in the upper reservoir during each hour is larger than predicted values, indicating that the actual wind power output is larger than the predicted value at most time. Fig.2. (b), during time periods 1:00-5:00 and 9:00-11:00, the extra wind power output is employed by the pumped-storage hydro plant to

pump water. During 6:00-7:00, a decrease in the pumping capacity of the pumped-storage hydro plant means the shortage of wind power output. In Fig.2(c), when the pumped-storage hydro plant operates in generating mode, the plant has to generate more to compensate the shortage of wind power output during 12:00-16:00 and generate less during 17:00-23:00.

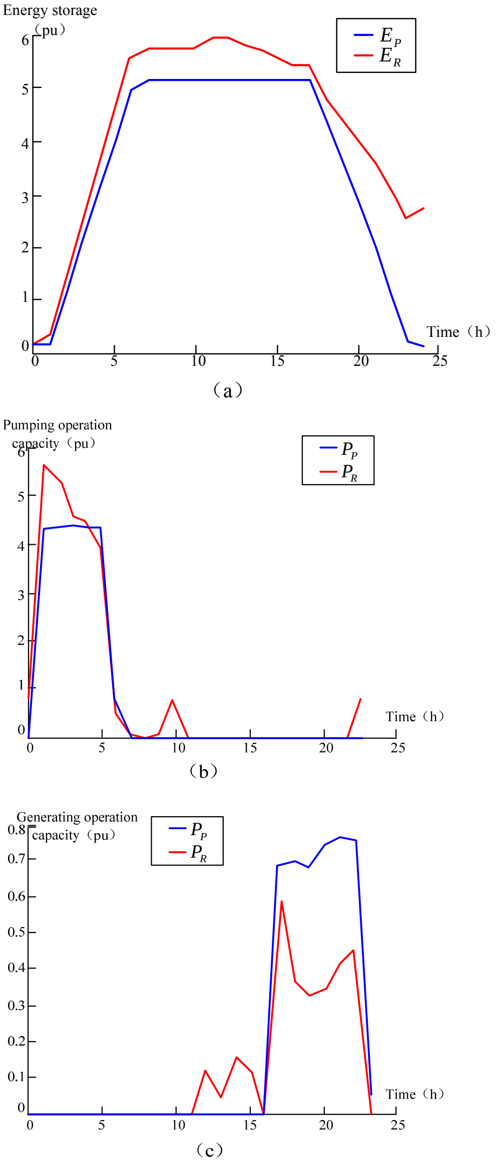

Fig.2. Comparison between actual operation curve and planning curve calculated by joint operation model

Based on the seasonal characteristics of wind power output, the economic benefits of the joint operation in summer and winter are treated differently. Curves about the feed-in tariff and reserve capacity price of the joint operation on typical days in summer and winter are described in Fig.3 and Fig.4.

From Fig.4, on working days and Saturday in winter, reserve capacity of the joint operation cannot entirely compensate the deviations from wind power output at most time so the wind farm should purchase reserve capacity at the ancillary service market. Note that the pumped-storage hydro plant can merely compensate 90% of the deviations. Instead, on Sunday, the wind farm has sufficient capacity which can be sold at the ancillary service market. In summer, both extra capacity and insufficient capacity may occur on working days and Saturday while an obvious shortage in the capacity occurs on Sunday.

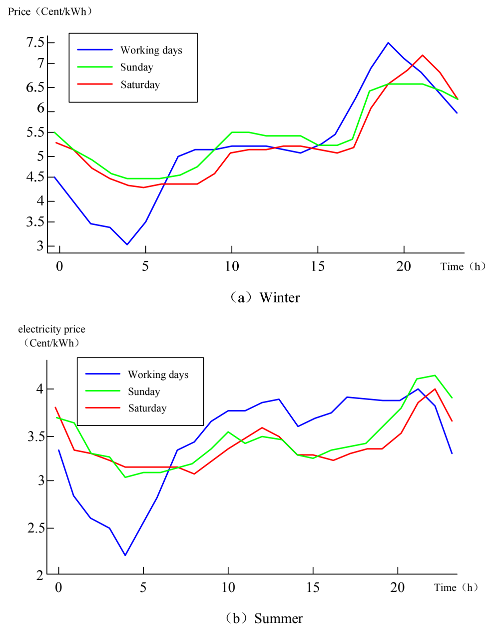

Fig.3. Feed-in tariff curve in winter and summer

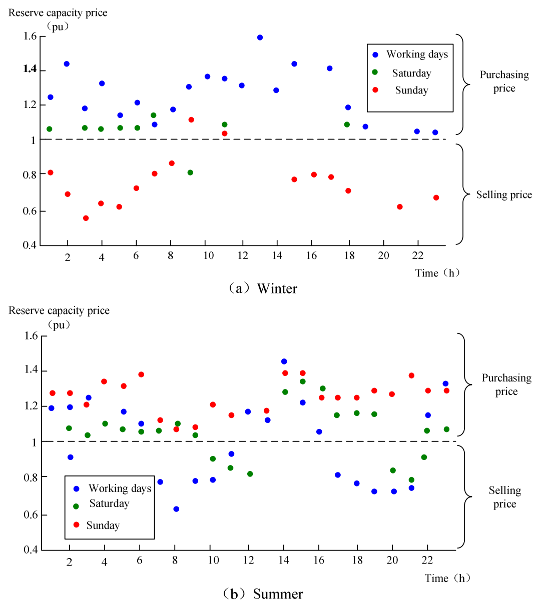

Fig.4. Reserve capacity price curve in winter and summer

With the actual operation data, independent and joint operation model are used to determine the economic benefits on typical days in summer and winter. The comparative analysis is applied to the two operation modes. Calculation results are shown in Table 1 and Table 2.

For example, on the working days in winter, the economic benefits of the pumped-storage hydro plant in independent operation mode reach €4375 ((1)-(8)). Nevertheless, the economic benefits of the pumped-storage hydro plant in joint operation mode are €3097 ((9)-(16)), decreasing by 29.2%.

The reason is that the operating generation capacity declines in accordance with the improvements of the constraints in joint operation model. And the gap of the benefits is actually the opportunity costs of the pumped-storage hydro plant. The total benefits of the joint operation are actually €24419, increasing by 9.7% due to revenues from the wind power generation and auxilliary service market ((17)-(20)).

Table 1. Economic benefits of independent and joint operation in winter

Revenues（€）		Typical days		
		Working days	*Sunday*	*Sunday*
Independent operation	Pumped-storage hydro plant	4375	1446	2209
	Wind farm	17888	29316	17333
	Total	22263	30762	19542
Joint operation	Pumped-storage hydro plant	3097	1172	1466
	Opportunity costs	-1279	-274	-743
	Growth rate of opportunity costs(%)	-29.22	-18.9	-33.6
Actual revenues under joint operation		24419	37076	23465
Added revenues		2156	6314	3923
Growth rate of revenues(%)		9.7	20.5	20.1

Table 2. Economic benefits of independent and joint operation in summer

Revenues（€）		Typical days		
		Working days	*Sunday*	*Sunday*
Independent operation	Pumped-storage hydro plant	1231	157	31
	Wind farm	10817	11183	10943
	Total	12048	11340	10974
Joint operation	Pumped-storage hydro plant	898	-72	-334
	Opportunity costs	-333	-229	-365
	Growth rate of opportunity costs(%)	-27.0	-145.5	-1185.9
Actual revenues under joint operation		15301	13582	14672
Added revenues		3253	2242	3698
Growth rate of revenues(%)		27.0	19.8	33.7

The added revenues are much more obvious on other typical days. In summer, the economic benefits of the pupmed-storage hydro plant in joint operation are negative due to the mild electricity price curve. Instead, the total economic benefits of the joint operation rise substantially (27.0% 、 19.8% 、 33.7%), which indicates that it is beneficial to employ the pumped-storage hydro plant to compensate the devirations from wind power output.

Conclusions

In this paper, the joint operation mode of the pumped-storage hydro plant and the wind farm was proposed to deal with the deviations between the actual wind power output and the predicted values, which contributes a lot to mitigating the negative impact of wind power integration on the power gird, reducing the operation risks and improving economic benefits. Technically speaking, the optimal operation mode obtained in the joint operation model can compensate the deviations from wind power output. As for the economic benefits, it seems that the pumped-storage hydro plant has opportunity costs, but the total revenues in joint operation are larger than those in independent operation in the consideration of the stable wind power output. In addition, the added revenues in the joint operation can be allocated between the pumped-storage hydro plant and the wind farm by signing contract, which can partially compensate the opportunity costs of the pumped-storage hydro plant.

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