Analysis of hybrid wind-photovoltaic-hydro generation system based on short-term scheduling

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Abstract. Renewable energy sources are beneficial to provide clean power generation but simultaneously brings power supply risk due to natural uncertainties. A hybrid wind-solar-hydro generation system, which takes advantage of the complementary characteristic of renewable energy sources, is capable to supply the power demand reliably. A multi-objective model of the hybrid system is proposed to achieve minimum power supply risk and maximum economic benefit under natural limitations. To handle natural uncertainties, autoregressive integrated moving average model is applied to produce typical daily models of weather conditions in different scenarios. Meanwhile, particle swarm optimization algorithm is improved to solve the multi-objective model by introducing the ε-constraint method. Lastly, an example of a large-scale hybrid wind-photovoltaic-hydro system is given to analyse reliability, profit, efficiency and operation in different scenarios. The study has shown that the hybrid system does not crash reliability but increases economic benefit, it’s necessary to reserve wind and solar generation, wind generation needs to cooperate with hydro generation according to water dispatching.

1. Introduction

Renewable energy sources (RES), such as wind, solar and wave, are replacing traditional fossil fuels gradually to provide environment-friendly power generation, which benefits energy-saving and emission-reduction [1]. Natural uncertainties of RES result in unpredictable power supply risk with high penetration of RES. Due to the complementarity of RES, output fluctuation of RES can be alleviated by scheduling RES appropriately [2].

Research regarding to RES focuses on two aspects: analysis of RES to improve reliability of power supply, optimal scheduling strategies for integrating RES with current grid. A. Solomon et al. demonstrated that hydro wind-solar generation system has multiple advantages compared with independent wind or solar generation system due to the complementarity of wind and solar [3]. R. Karki et al. proposed a reliability evaluation method for wind-hydro generation based on Monte Carlo simulation [4]. Bo Ming et al. established photovoltaic-hydro model to maximize energy production and minimize water consumption [5]. Jie Li et al. applied multi-objective dragonfly algorithm to achieve...
short-term optimal scheduling for hybrid wind-solar-hydro generation [6]. Hu Wei et al. improved deep neural network to track the power demand for variable hybrid generation systems [7]. However, in terms of hybrid wind-solar-hydro generation system, while such researches have explored flexible scheduling strategies to deliver higher and steadier power generation, few have taken reliability and economic benefit into considerations simultaneously under natural limitations and water dispatching.

This study focused on the optimal scheduling of the hybrid wind-photovoltaic-hydro generation system considering natural uncertainties. A multi-objective optimization model for short-term scheduling was established to balance power supply risk and economic benefit. Particle swarm optimization with the ε-constraint method was introduced to give decisions after using autoregressive integrated moving average model to handle natural uncertainties, and eight typical scenarios were discussed to give propositions for operating the hybrid system.

2. Modelling

2.1. Minimize power supply risk

Natural uncertainties existing in RES, such as wind speed, solar radiation, and water flow, cause power supply risk of the hybrid wind-photovoltaic-hydro generation system. From electric and economic perspectives, a reliable power supply is expected to meet the power demand within the designed boundaries. Therefore, the objective of minimizing power supply risk is to make the total output power close to the power demand.

Let \( P_w \), \( P_s \) and \( P_h \) represent the output power of wind turbine, solar array and hydro turbine at time \( t \) respectively, \( D_t \) represent the power demand at time \( t \), \( \Delta P \) represent the difference between the total output power of hybrid generation and the power demand, the objective of minimizing power supply risk can be written as:

\[
\min f_1 = |\Delta P|
\]

(1)

\[
\Delta P = \sum_{w=1}^{n} P_w + \sum_{s=1}^{k} P_s + \sum_{h=1}^{m} P_h - D_t
\]

(2)

2.2. Maximize economic benefit

Economic dispatching (ED) is commonly used to achieve maximum profit [8], however it’s insufficient to our hybrid system. According to Report of statistics of on-grid prices of China in 2018 [9], average on-grid prices of wind, photovoltaic (PV), hydro and coal-fired are 529.01, 859.79, 267.19 and 370.52 CNY per MWh respectively. If coal-fired generation, as another energy source, is assumed to supply the demand with the hybrid system simultaneously in case of power shortage, there will be no hydropower due to higher price of coal-fired generation. Therefore, weight multipliers instead of prices are used to carry out ED. Let \( C_w \), \( C_s \), \( C_h \) and \( C_o \) represent weight multipliers of wind, solar, hydro and another energy source respectively, the optimal dispatching to maximize economic benefit can be expressed as:

\[
\max f_2 = \sum_{w=1}^{n} P_w C_w + \sum_{s=1}^{k} P_s C_s + \sum_{h=1}^{m} P_h C_h + A C_o
\]

(3)

\[
A = \begin{cases} 0, & \Delta P \geq 0 \\ \Delta P, & \Delta P < 0 \end{cases}
\]

(4)

An energy source with larger weight multiplier, regardless of exact value, has higher priority in the dispatching, but \( C_o \) should be the largest as penalty at any time. For instance, only the relationship \( C_w > C_s > C_h > C_o \) needs to be guaranteed in the previous case. Particularly, \( A \) means that there is no reward if exceeding the power demand but there is penalty if the power demand isn’t met. One advantage of weight multipliers is able to dispatch each generation unit flexibly. For instance, there are two exactly
same hydro turbines $h_1$ and $h_2$, which lead to ambiguity in decisions. The clear decision of both turbines can be obtained by adding $C_{a1} > C_{a2}$ or $C_{a1} < C_{a2}$ locally.

2.3. Wind Generation Modelling
Let $P_w$ represents the rated output power of wind turbine $w$, $v_{mw}$ and $v_{mmax}$ represent minimum wind speed for power generation and maximum wind speed for protection respectively, $v_{wr}$ represents wind speed at the rated output power, $x_w$ represents wind turbines operated at time $t$, the output power of wind generation at time $t$ [10] can be written as:

$$P_w = \begin{cases} 0, & v_{wr} < v_{mw} \text{ or } v_{wr} \geq v_{mmax} \\ P_{max}x_w, & v_{mmin} \leq v_{wr} < v_{mmax} \end{cases}$$

(5)

2.4. PV Generation Modelling
Let $P_{s0}$ represents the rated output power of PV array $s$, $I_s$ represents solar radiation received by PV array $s$ at time $t$, $I_{std}$ represents solar radiation under the standard test conditions, $\alpha_t$ represents de-rating factor due to temperature, $T_s$ represents the effective cell temperature at $t$, $T_0$ represents the cell temperature under the standard test conditions and $y_s$ represents PV arrays operated at time $t$, the output power of PV generation at time $t$ [10] can be written as:

$$P_s = \min \left\{ P_{s0} \frac{I_s}{I_{std}} \left[1 + \alpha_t(T_s - T_0)\right], P_{s0}y_s \right\}$$

(6)

Because $T_s$ is influenced by multiple factors, such as ambient temperature, solar radiation, wind speed and dust on the surface, it’s difficult to calculate exact $T_s$. Only solar radiation is considered to correct $T_s$ from ambient temperature in this paper, the correction of $T_s$ [10] can be written as:

$$T_s = T_0 + \frac{I_s}{1000} \left( \frac{T_0 - 20}{0.8} \right)$$

(7)

2.5. Hydro generation modelling
Let $w_h$ represents water released through hydro turbine $h$ during time $t$, $E_{min}^h$ and $E_{max}^h$ represent minimum and maximum water release rate during time $t$ respectively, $\eta_h$ represents the comprehensive efficiency of hydro turbine $h$, $g$ is the specific weight of water ($g = 9.81 kN/m^3$ in normal), $H$ represents water head, $P_{s0}$ represents the rated output power of hydro turbine $h$ and $z_{hi}$ represents operation status of hydro turbine $h$ during time $t$, where $z_{hi} = 1$ if hydro turbine $h$ is on and $z_{hi} = 0$ if hydro turbine $h$ is off, the output power of hydro turbine $h$ during time $t$ [11] can be written as:

$$P_h = \begin{cases} 0, & w_h < E_{min}^h z_{hi}, \text{ } E_{min}^h z_{hi} \leq w_h < E_{max}^h z_{hi} \\ \eta_h g w_h H z_{hi}, & E_{max}^h z_{hi} \leq w_h \end{cases}$$

(8)

2.6. Dynamic process in the reservoir
There are two components of water in the reservoir: natural water flow into the reservoir and water released by hydro turbines. It’s noted that pumped water will be included if the energy conservation system is considered, which is ignored in this paper. Let $F_n$ represents natural water flow during time
$t$, $\Delta t$ represents time duration which is equal to 3600s in this paper due to hourly modelling, water left in the reservoir at the end of time $t$ can be written as:

$$R_t = R_{t-1} + F_t \Delta t = \sum_{i=0}^{n} \sum_{i=0}^{m} w_{ii} \Delta t$$ (9)

Water left in the reservoir should satisfy the limitation of water storage, let $V_{\text{min}}$ and $V_{\text{max}}$ represent minimum and maximum water storage for power generation respectively, water storage limitation can be written as:

$$V_{\text{min}} \leq R_t \leq V_{\text{max}}$$ (10)

Some papers [6, 11] apply the form

$$Q_{\text{min}} \leq \sum_{i=0}^{n} \sum_{i=0}^{m} z_{ii} w_{ii} \Delta t \leq Q_{\text{max}}$$ as available water limitation, in which $Q_{\text{min}}$ and $Q_{\text{max}}$ are minimum and maximum available water for power generation. However, Eq. (10) can be obtained by transforming available water limitation.

2.7. Constrains of power transmission

There are line and stability constraints that must be satisfied to meet the upper bound of transmission capability and avoid the rapid fluctuation of output power of each power plant [8]. Let $P_{pi}$ represents the output power of power plant $p$ at time $t$, $P_i$ represents the upper bound of transmission line $l$, line constraints can be expressed as:

$$P_{pi} \leq P_i$$ (11)

Let $P_{\text{min}}^p$ and $P_{\text{max}}^p$ represent the lower and upper bound of stability of power plant $p$ at time $t$, stability constraints can be expressed as:

$$P_{\text{min}}^p \leq |P_{pi} - P_{p,i-1}| \leq P_{\text{max}}^p$$ (12)

2.8. Time sequence processed by ARIMA

To handle natural uncertainties ($v_w$, $i_a$, $T_{\text{ar}}$ and $F_r$), autoregressive integrated moving average (ARIMA) model is applied to produce their typical hourly models in different scenarios. The mathematical expression of ARIMA is:

$$\nabla y_t - \sum_{j=1}^{p} \theta \nabla y_{t-j} = \alpha_t - \sum_{j=1}^{q} \theta \alpha_{t-j}$$ (13)

The procedure of applying ARIMA is briefly described in the following steps:

Step 1. Test the stationarity of the input time sequence by Augmented Dickey–Fuller (ADF) test;

Step 2. Apply differential processing on the sequence until passing ADF test;

Step 3. Generate ARIMA models with different order $p$ and $q$ within their limited extents;

Step 4. Evaluate these ARIMA models with Akaike Information Criterion (AIC);

Step 5. Choose ARIMA model with minimum AIC to produce typical time sequence.

3. Model solved by PSO algorithm with the $\varepsilon$-constraint method

Particle swarm optimization (PSO) algorithm, based on the act of birds searching for food, was introduced to solve mathematical optimization problems by Eberhart and Kennedy in 1995 [12]. Let $X_{di}$ and $V_{di}$ represent the position and velocity of particle $d$ in iteration $i$, $P_{di}$ records the best position of particle $d$ until iteration $i$, $P_g$ records the global best position of all particles in iteration $i$, $\omega$ is inertia factor which is decreased from 0.5 to 0.1 according to iterations in this paper, $C_i$ and
C_t are accelerated velocities (both are equal to 1.5 in this paper) and rand represents random number subject to $U[0,1]$, the process of PSO can be expressed as:

$$V_{i+1,d} = \omega V_{i,d} + C_1 rand(P_{i,d} - X_{i,d}) + C_2 rand(P_{g,d} - X_{i,d})$$

$$X_{i+1,d} = X_{i,d} + V_{i+1,d} \tag{14}$$

Because PSO algorithm cannot deal with multiple evaluation functions, PSO algorithm only works for a single objective model. In order to solve the multi-objective model proposed in Section 2, we use the $\varepsilon$-constraint method to transform a multi-objective optimization to a single objective optimization \cite{13}. In the $\varepsilon$-constraint method, one of objective functions is chosen as the main objective function, and the remaining objective functions are treated as constraints. $x$ is the vector of variables, $S$ is the feasible region and $f_i(x)$ is the $ith$ objective function considered as a constraint, the transformation in the $\varepsilon$-constraint method can be written as:

$$\max/\min f(x)$$

$$s.t. \begin{cases} f_1(x) \geq \varepsilon_1 & \text{for max function} \\ f_2(x) \leq \varepsilon_2 & \text{for min function} \\ \ldots \\ f_n(x) \geq \varepsilon_n \\ x \in S \end{cases} \tag{15}$$

Eq. (3) is chosen as the main objective function and Eq. (1) is transformed to be constraint. There is alternation for the constraint transformed from Eq. (1), $f_i(x) \leq \varepsilon_i$ is revised to be $f_i(x) \leq m\varepsilon_i$, where $m$ represents incremental multiplier and $\varepsilon_i$ represents incremental step. The optimal decision will make Eq. (1) close to 0. However, if a fixed constraint $\varepsilon_i$ is used to iterate, PSO will make Eq. (1) close to $\varepsilon_i$ when $\varepsilon_i \geq 0$ because there is positive correlation between Eq. (1) and Eq. (2). A dynamic constraint $m\varepsilon_i$, whose extent is gradually narrowed in iterations, is able to avoid the previous circumstance. On the other hand, there may be no particle under the condition $f_i(x) \geq \varepsilon_i$ during the initial iterations of PSO algorithm due to random positions, which induces the following iterations to be failure. But this situation disappears when the dynamic constraint $m\varepsilon_i$ replaces the fixed constraint $\varepsilon_i$. The detailed procedure of applying $m\varepsilon_i$ is to set $\varepsilon_i$ as an acceptable inaccuracy and increase $m$ from 0. Therefore, the mathematical model of the hybrid generation can be rewritten as:

$$\max f = \sum_{i=1}^{T} \left( \sum_{u=1}^{n} P_u C_u + \sum_{s=1}^{S} P_u C_s + \sum_{h=1}^{H} P_u C_h + A C_s \right)$$
Flowchart of PSO algorithm with the ε-constraint method is shown in Fig. 1. Firstly, $X_{id}$ and $V_{id}$ are initialized by random values within their corresponding boundaries. Eq. (5–9) are used to calculate the output power of each energy source and water storage. In the next stage, the validity of $X_{id}$ is verified by checking whether $X_{id}$ meets inequalities Eq. (10–12). $E(X_{id})$ represents the validity, where $E(X_{id})=1$ if $X_{id}$ is valid, otherwise $E(X_{id})=0$. Commonly, equalities are directly used to calculate, inequalities are used to determine the validity of particles.

In updating $P_{id}$, valid $X_{id}$ always replaces invalid $P_{id}$ with ignoring $f(X_{id})$. Otherwise, $P_{id}$ is replaced by $X_{id}$ under the conditions $\lvert \Delta P_{id}(X_{id}) \rvert \leq m \Delta$ and $f(X_{id}) \geq f(P_{id})$ when $E(X_{id})=E(P_{id})$. In the next stage, $P_{id}$ is determined with the valid $P_{id}$ when $f(P_{id})$ reaches maximum under the condition $\lvert \Delta P_{id}(P_{id}) \rvert \leq m \Delta$. Sometimes there is no valid $P_{id}$ during initial iterations, the above rule ignoring validity can also be applied to keep on iterating.

The reason why not apply $\lvert \Delta P_{id}(X_{id}) \rvert \leq \lvert \Delta P_{id}(P_{id}) \rvert$ and $f(X_{id}) \geq f(P_{id})$ is that $\lvert \Delta P_{id}(X_{id}) \rvert \leq \lvert \Delta P_{id}(P_{id}) \rvert$ is too strict to update $P_{id}$. Let’s consider a case that $\Delta P_{id}(P_{id}) = 0.1$, $f(P_{id}) = 0.1$ and $\Delta P_{id}(X_{id}) = 0.1001$, $f(X_{id}) = 1$ where both $\Delta P_{id}$ and $f$ are normalized. Definitely, $P_{id}$ should be updated by $X_{id}$, however, $X_{id}$ is rejected since the condition $\lvert \Delta P_{id}(X_{id}) \rvert \leq \lvert \Delta P_{id}(P_{id}) \rvert$ isn’t satisfied. The same reason also accounts for applying $\lvert \Delta P_{id}(P_{id}) \rvert \leq m \Delta$ in finding $P_{id}$. It’s noted that a relatively small $\Delta$ leads to the fact that the objective $f$ is ignored, which implies that making $\lvert \Delta P_{id} \rvert$ close to 0 is the first priority. In order to reduce the computational burden, $m$ can be increased nonlinearly when $m$ exceeds the threshold.

Lastly, Eq. (14) is used to update the position and velocity of particles, and the termination criteria (maximum iterations) is judged.
Figure 1. Flowchart of PSO algorithm with the $\varepsilon$-constraint method

4. Case study
In this section, a hybrid wind-PV-hydro generation example is given to evaluate reliability, economic benefit and efficiency of RES. To handle natural uncertainties mentioned in Section 2.1, different scenarios, as shown in Table 1, are presented to provide a comprehensive comparison.

| Scenario | Description          | Scenario | Description          |
|----------|----------------------|----------|----------------------|
| 1        | breeze, cloudy, dry  | 5        | breeze, cloudy, flood|
| 2        | normal, cloudy, dry  | 6        | normal, cloudy, flood|
| 3        | breeze, sunny, dry   | 7        | breeze, sunny, flood  |
| 4        | normal, sunny, dry   | 8        | normal, sunny, flood  |

The prototype of the hybrid system is Longyang Gorge hybrid PV-hydro generation system, where a hypothetical wind farm replaces a 320MW hydro turbine. Therefore, our hybrid wind-PV-hydro generation system consists of a 320 MW wind farm, an 850 MW PV plant and a 960 MW hydro plant, where the rated output power of wind turbine, PV array and hydro turbine are 2 MW, 1 MW and 320 MW respectively. Parameters of wind turbines are collected from [10], parameters of PV arrays and hydro turbines are gathered from [14]. It’s assumed that $\delta$ is set as 1 MW, initial water head is 133 m in all scenarios where the corresponding water storage is 18.5 billion m$^3$, prices mentioned in Section 2.2 which leads to $C_p > C_1 > C_s > C_4 > C_2 > C_3$ are used to calculate earnings. Wind farm, PV plant and hydro plant are assumed to be under the same management and located within the relatively short
geographical distances, an external system is assumed to supply the gap in case of power shortage. The structure of the hybrid system is shown in Fig. 2.

Figure 2. Structure of the hybrid system

Output offset degree (OOD) presented in Eq. (15) [10], which indicates the offset degree between the total output power and the power demand, is used to evaluate reliability.

\[
OOD = \sqrt{\sum_{t=1}^{T} \left( \frac{\Delta P_t}{D_t} \right)^2}
\]

Weather data, including wind speed, solar radiation, ambient temperature, natural water flow, are gathered from National Meteorological Center [15], all of which are processed by ARIMA to produce corresponding typical daily models. Typical daily power demand data in the dry and flood season are collected from [11].

4.1. Calculation results and analysis

In the dry season, 2 hydro turbines are allocated to undertake 400 MW base load. In the flood season, the base load is adjusted to 600 MW, which is shared by 3 hydro turbines. Fig. 3 shows scheduling decisions determined by PSO algorithm with the ε-constraint method in 8 scenarios. Due to uncertainty in wind speed, hydro output power is less smooth in scenarios 1, 3, 5, 7 compared with scenarios 2, 4, 6, 8. Similarly, uncertainty in solar radiation leads to hydro output power more fluctuant comparing scenarios 1, 2, 5, 6 and scenarios 3, 4, 7, 8. It draws our attention that there is almost no wind output power during time 13~17 in scenarios 3, 4, 7, 8 because the base load of hydro generation is fixed at a relatively high level and the output power is abundant in PV generation.

Figure 3. Hourly power supply and demand of different scenarios
According to Table 2, it can be concluded that difference between peak and valley of hydro power is mainly determined by wind generation, uncertainties in both wind and solar generation work together to increase daily accumulated fluctuation of hydro power but wind generation is responsible for the majority. Therefore, wind generation is more important than solar generation for integrating with hydro generation considering operation of hydro turbines.

### Table 2. Statics of hydro output power

| Scenario | Hydro power | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Peak-valley (MW) | | | | | | | |
| 1 | 378 | 243 | 378 | 243 | 344 | 212 | 344 | 212 |
| 2 | 1161 | 888 | 1020 | 727 | 981 | 695 | 944 | 586 |

From Fig. 4, $\Delta P_t$ which is the gap supplied by the external system ranges from -0.705 MW to 0.999 MW in 8 scenarios, there is no result out of the boundary set as 1 MW in the $\varepsilon$-constraint method, which means that all results are acceptable in terms of power supply risk.

![Figure 4. $\Delta P_t$ in 8 scenarios](image)

As presented in Table 2, different scenarios have almost no influence on OOD (0.056%–0.071%), which demonstrates that RES do not get the reliability of power supply to crash. However, different scenarios affect economic benefit dramatically and solar generation is more significant than wind generation to increase economic benefit. In terms of the efficiency of utilizing RES, wasted solar energy is much less than wasted wind energy in each scenario because maximizing economic benefit gives priority to solar generation. Wind and solar energy in scenarios 3, 4, 7, 8 are extremely wasted due to low power demand during time 13–17, which is also indicated in Fig. 3.

### Table 3. Comparison of different scenarios

| Scenario | OOD | Price (CNY ¥) | Wasted energy (MWh) | Wasted energy (MWh) | $\Delta R_s/R_{s,1}$ |
|---|---|---|---|---|---|
| | | | | | |
| 1 | 0.071% | 9,579,862 | 115.43 | 1.82 | -0.028% |
| 2 | 0.063% | 10,115,819 | 507.27 | 2.99 | 0.005% |
| 3 | 0.064% | 10,336,227 | 666.10 | 227.06 | -0.012% |
| 4 | 0.059% | 10,774,763 | 1428.98 | 229.25 | 0.015% |
| 5 | 0.063% | 10,730,468 | 114.13 | 2.24 | 0.061% |
| 6 | 0.056% | 11,232,953 | 635.62 | 2.00 | 0.092% |
| 7 | 0.066% | 11,426,033 | 771.46 | 285.27 | 0.074% |
| 8 | 0.060% | 11,845,410 | 1598.89 | 288.98 | 0.100% |

Apart from power generation, the reservoir also undertakes other responsibilities, such as water supply, irrigation and anti-flooding, which are also crucial to social and economic development. Especially, water reservoir is often faced with abnormal water scheduling due to the contradiction of
water consumption and unbalanced water resource distribution [16], which seriously interferes with hydro generation. Hence, the strategy of scheduling hydro generation should be adjusted to adapt water dispatching in the dry and flood season respectively. Briefly, water consumption for power generation in the dry season is desired to be as little as possible, and water storage in the flood season is required to maintain at a given level in case of flooding. \( \Delta R_t/R_t - 1 \) represents variation ratio of water storage after a scheduling day. According to Table 2, water storage is reduced in scenarios 1, 3, water storage is slightly increased in scenarios 2, 4, water storage in the flood season are increased noticeably. Furthermore, wind generation rather than solar generation plays a major role in regulating water storage in different scenarios because solar generation undertakes the majority of load adjustment in the daytime. In the given example, if the base load can be adjusted, the base load in scenarios 1, 3 will be moderately decreased and the base load in the flood season will be further increased.

4.2. Propositions

There are three propositions drawn from the calculation results to demonstrate main conclusions.

Proposition 1: The hybrid system is able to improve economic benefit without ruining the reliability of power supply. Due to higher on-grid prices of wind and solar generation, power supplier’s revenue grows with penetration of RES. As presented in Section 4.1, OOD reaches the maximum value 0.071% during the breeze and cloudy time in the dry season but \( \Delta P_c \) is acceptable, which proves that the hybrid wind-PV-hydro generation system proposed in this paper still meets the power demand under the worst weather conditions. In addition, a better result can be guaranteed by setting \( \delta \) smaller. Although sudden changes in natural uncertainties may disrupt the reliability of the hybrid system, it can be mitigated by applying weather forecasting methods or adding energy storage systems, such as battery or pumped storage system.

Proposition 2: It’s unnecessary to seek to make full use of wind and solar generation when both are integrated with hydro generation. In scenarios 4 and 8, the complementarity of wind and solar generation is desired to smooth hydro output power without adjusting operation status of hydro turbines frequently. But this complementarity can be easily weakened by natural uncertainties as shown in other scenarios. Compared with scenarios 4 and 8, peak-valley and accumulated fluctuation of hydro power degenerate 55.8% and 59.7% in scenario 1, 62.1% and 67.5% in scenarios 5. If the base load is reduced to achieve higher efficiency of wind and solar generation, technical issues in hydro power dispatching will occur in scenarios 1 and 5 firstly and occur in other scenarios subsequently. But the power demand of time 13~17 in the flood season can be reasonably increased to avoid wasting excessive RES. Therefore, there is a trade-off between the efficiency of RES and the stability of hydro generation system.

Proposition 3: Wind generation needs to be carefully managed for integrating with hydro generation considering water dispatching. As discussed in Section 4.1, wind generation leads to regulating hydro output power frequently but is helpful to reduce water consumption in the dry season. Additionally, hydro generation expects to be increased to maintain water storage in the flood season, which results in wasting more wind energy. Therefore, wind and hydro generation are contradictory in terms of operating hydro turbines and managing water storage. Since a power system is not stand-alone to support social and economic development, there is no doubt that water dispatching is given top priority and hydro generation is determined according to water dispatching. To alleviate frequent regulations of hydro turbines in the dry season and lessen wasted wind energy in the flood season, optimal base load and power demand can be determined in the stage of planning based on our mathematical model.

5. Conclusion

This paper focuses on a hybrid wind-PV-hydro generation system, which is established by nonlinear multi-objective model to achieve reliable power supply and maximum economic benefit. ARIMA is adopted to produce typical daily distributions of wind speed, solar radiation, ambient temperature and water flow. To solve the multi-objective model, PSO algorithm is improved by introducing the \( \epsilon \)-constraint method, in which the multi-objective optimization is transformed into the single objective optimization. Scheduling decisions of a large-scale example are comprehensively discussed to optimize
the hybrid system for power supplier, in which other social and economic responsibilities, including water supply, irrigation and anti-flooding, are considered.

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