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# **Operation Flexibility Evaluation and Its Application to Optimal Planning of Bundled Wind-Thermal-Storage Generation System**

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**Abstract:** The growing penetration of wind power in a power system brings great challenges to system operation flexibility. For generation planning in presence of high wind power penetration, it is essential to take the operation flexibility of the system into account. Firstly, this paper developed the system operation flexibility metrics through considering the flexibility contribution of thermal generating units (TGUs) by operational state transition. Secondly, a planning model for the bundled wind-thermal-storage generation system (BWTSGS) that considers the operation flexibility constraints is proposed. The planning model is used to determine the power and energy rating of an energy storage system (ESS) as well as the type and number of TGUs. A daily scheduling simulation model of a BWTSGS is proposed to calculate the operation cost for the planning model and consider the sequential operation characteristics of the BWTSGS. Further, in order to accelerate the computation, a wind power sequential clustering technique based on the discrete Fourier transform (DFT) method is developed for improving the computational efficiency. Case studies have been conducted on a 1000-MW wind farm to demonstrate the validity and effectiveness of the proposed model.

**Keywords:** operation flexibility; wind-thermal generation; energy storage system; generation planning; scheduling simulation

# 1. Introduction

The development of wind power has been accelerating in recent years to cope with the growing energy consumption as well as the environmental deterioration [1]. Two common ways are available to integrate wind power to the grid. One is distributed integration, in which wind power is accommodated by the local electric distributed network directly [2]. Another is centralized integration, in which most of the wind powers is delivered from wind farms directly to load centers [3]. For areas with rich wind resources, but geographically far from high-demand load centers, light load demand severely restricts the consumption level of wind power. As a result, a significant amount of wind energy may be wasted. For such areas, it would be economically efficient to transmit the wind power to load centers [4].

However, the small equivalent capacity and high volatility of wind power makes the direct transmission of large-scale wind power cost ineffective, and poses challenges to the receiving power system [5]. Since the wind-rich areas are usually close to areas with rich coal reserves, recent researches have proposed the idea of bundled wind-thermal generation systems (BWTGS) [6]. Scheduling thermal generating units (TGUs) to mitigate the variability of wind power can increase the capacity factor of the transmission facilities and alleviate the risk of the receiving system [6].

In addition, the high penetration of wind power in a power system brings great challenges to system adequacy, security, and operation flexibility. The operation flexibility describes the ability of a power system to deploy its resources in response to the changes in system load and variable generations (VGs) [7]. With increased wind power penetration, system flexibility has become a critical factor to maintain the load generation balance for system operators. It is also important to consider the flexibility in generation planning in presence of high wind power penetration [8].

Many studies have been conducted on the BWTGS and the evaluation of operation flexibility.

By investigating the uncoordinated development of wind power and the lagging development of transmission systems, Ni and Yang [6] concluded that the planning of BWTGS is an effective way to develop the wind energy resources. In [9], Xie et al. proposed an optimal BWTGS planning method that considered the operational constraints of matched TGUs and generation system. The planning of HVDC-based bundled wind-thermal generation and transmission system has also been investigated [5]. Chen et al. [10] investigated the transient characteristics of AC/DC transmitted BWTGS under the case of a DC block fault, and the results obtained provides valuable information for the future search of transient stability of the wind-thermal bundled transmission system. In [11], a model to optimize the generation maintenance schedule for BWTGS is proposed. The probabilistic production simulation technique was employed to calculate the system costs, and a sequential probabilistic method was utilized to capture the sequential and stochastic nature of wind power. Although researches regarding the BWTGS have been well studied, to the best of our knowledge, no previous work has been reported on the consideration of operation flexibility in BWTGS planning.

A number of researches on the system operation flexibility have also been reported. In [7], the insufficient ramping resource expectation (IRRE) metric has been developed to assess power system flexibility from a probabilistic viewpoint. A flexibility index that reflects the individual generating unit and the whole system was proposed for incorporation into the unit construction and commitment model [12]. The flexibility envelope that describes the flexibility potential dynamics of a power system and individual resources was introduced in [13]. The flexibility of aggregated demands for retail consumers was studied and an optimization model was built to determine the load scheduling for aggregated demands [14].

Most of the flexibility related researches for generation planning were conducted based on the spinning reserve requirement, and did not consider the state transition of generating units. Yet in practice, the high penetration of renewable energy resources (RESs)could lead to the frequent start-up and shut-down of generating units [14]. Assuming that only the synchronized generators are able to respond to the fluctuation of variable generations (VGs), the operation and planning cost of generating units would be thereby increased. Thus it is inappropriate to evaluate the system flexibility without considering the state transition of generating units.

The bundled delivery of wind and thermal power is an effective way for the utilization of wind energy resources. However, the matched TGUs in BWTGS may have difficulty coping with the volatile wind power. Under this circumstance, more TGUs are required, resulting in the increased operation and planning costs [15]. The energy storage system (ESS) can store and release electric energy quickly [16] and can mitigate the variability of renewable energy resources (RESs). The integration of ESS into the bundled generation system may alleviate the operation difficulty that is encountered by the matched TGUs and make the bundled delivery more efficient. Figure 1 depicts the configuration of a bundled wind-thermal-storage generation system (BWTSGS).

Many researches have been conducted on the operation and planning of ESS. In [15], a storage control policy to the limit ramp rates of wind power was studied so as to reduce the required amount of ancillary services. A planning approach was proposed to calculate the optimal location and size of an ESS considering the uncertainty of wind power [17]. A model that determined the optimal size of an ESS in a micro-grid with reliability constraints was developed [18]. A nondeterministic model for joint transmission and ESS expansion planning was examined in [19].



Figure 1. Configuration of a bundled wind-thermal-storage generation system (BWTSGS).

In this paper, firstly, the system operation flexibility metrics are developed. The flexibility contribution of TGUs by operational state transition is taken into account. Secondly, an optimal planning model of the BWTSGS considering operation flexibility constraints is proposed to determine the optimal power and energy rating of an ESS as well as the type and number of TGUs. A daily scheduling simulation model based on linear programming is also proposed to take into account the sequential operation characteristics of a BWTSGS. The operation flexibility constraints are devised to guarantee the security operation of a BWTSGS. In addition, a wind power sequential clustering technique based on the discrete Fourier transform (DFT) method is developed to improve the computation efficiency. Case studies using the historical wind data are presented to illustrate the effectiveness of the proposed model. The impacts of multiple factors, such as the flexibility constraints, ESS integration, target flexibility, and ESS cost, on the optimal planning scheme and operation cost of BWTSGS are also evaluated in this paper.

## 2. Power System Operation Flexibility

### 2.1. Definition of Power System Operation Flexibility Metrics

The operation flexibility of power system is defined as the ability to respond to the variability and uncertainty in power system, where the variability and uncertainty usually arise from the variable generations and the load demand.

For a BWTSGS, the transmission power (i.e., the load demand) is usually set as a constant to raise the utilization of the facilities. As shown in Figure 2, if the system operates without sufficient flexibility resources to respond to the variability and uncertainty of wind power, the system operator would be compelled to curtail the power output of wind energy or transmission power to keep the balance between the generation and the load demand.



Figure 2. Schematic of operation flexibility for the BWTSGS.

A BWTSGS can be considered as a relatively isolated power system. The operation flexibility metrics for BWTSGS are proposed to measure the ability of a BWTSGS to cope with the variability and

uncertainty of wind power. As the hourly variability of wind power contains abundant information of importance in the context of generation operation and planning [12], the flexibility metrics in this paper are on an hourly basis.

In practice, wind power at the next hour is uncertain and depends on the initial condition [20]. Thus, given the wind power at hour *t*, wind power at the next hour can be represented by a random variable. Its probability distribution function (PDF) could be obtained by the statistical analysis of historical wind data based conditional probability method [20]. It is supposed that the PDF of wind power at the next hour is  $f_W^{\kappa+1}(P_W(t+1))$ , as shown in Figure 2. Thereby, the system operation flexibility metrics are defined as follows.

Upward Operation Flexibility Insufficient Probability (*OFIP*<sup>up</sup>) is the probability that the system upward flexibility resources cannot cope with the wind power decline leading to the decrease of transmission power. *OFIP*<sup>up</sup> can be calculated by Equation (1)

$$OFIP^{\rm up}(t) = \int_0^{P_{\rm W}(t) - F_{\rm sys}^{\rm up}(t)} f_{\rm W}^{t+1}(x) dx,\tag{1}$$

where  $P_W(t)$  is the wind power at hour *t*;  $F_{sys}^{up}(t)$  is the system upward flexibility resources at hour *t* (MW); and  $f_W^{t+1}(x)$  is the PDF of wind power in the next hour.

Equation (1) can be also expressed as

$$OFIP^{\rm up}(t) = \Pr\Big\{\mathcal{P}_{\rm W}(t+1) \le P_{\rm W}(t) - F_{\rm sys}^{\rm up}(t)\Big\},\tag{2}$$

where  $\mathcal{P}_{W}(t+1)$  is the random wind power at hour t + 1.

Downward Operation Flexibility Insufficient Probability (*OFIP*<sup>do</sup>) is the probability that the system downward flexibility resources cannot cope with the wind power increase resulting in the curtailment of wind power. *OFIP*<sup>do</sup> can be calculated by Equation (3)

$$OFIP^{do}(t) = \int_{P_{W}(t) + F_{sys}^{do}(t)}^{+\infty} f_{W}^{t+1}(x) dx,$$
(3)

where  $F_{sys}^{do}(t)$  is the system downward flexibility resources at hour *t* (MW).

Equation (3) can be also expressed as,

$$OFIP^{do}(t) = \Pr\Big\{\mathcal{P}_{W}(t+1) \ge P_{W}(t) + F_{sys}^{do}(t)\Big\}.$$
(4)

#### 2.2. Evaluation of Power System Operation Flexibility

For a BWTSGS, the ESS and TGUs constitute the flexible resources responding to the variable high share of wind power. The flexibility contributed by the TGUs through transitioning operating states is considered in this paper.

## 2.2.1. TGU Flexibility Contribution

TGUs respond to the variable wind power either by performing in a spinning reserve manner or by changing their operating states via starting up or shutting down. The high share of wind power would make TGUs start up and shut down frequently to provide flexibility and response to the variability of wind power. The upward flexibility contributed by the *i*th TGU at hour *t* can be expressed as

$$F_i^{\rm up}(t) = \overline{P}_i^{+1}(t) - P_i(t) \tag{5}$$

$$0 \le \overline{P}_i^{+1}(t) \le P_{i,r}^{\max} \tag{6}$$

$$\overline{P}_i^{+1}(t) \le P_i(t) + RU_i \cdot U_i(t) + SU_i \times \left[\overline{U}_i^{+1}(t) - U_i(t)\right]$$
(7)

$$\overline{U}_i^{+1}(t) \le U_i(t) + \frac{1}{T_{i,\text{off}}^{\min}} \times \left[ T_{i,\text{off}}^{\min} - \sum_{n=0}^{T_{i,\text{off}}^{\min} - 1} U_i(t-n) \right]$$
(8)

$$\overline{U}_i^{+1}(t) \le U_i(t) + \left(1 + \frac{1 - T_i^{\text{startup}}}{\left|1 - T_i^{\text{startup}}\right|}\right)/2$$
(9)

 $\overline{P}_i^{+1}(t)$  is a nonnegative variable that represents the maximum available power output of the *i*th TGU in the next hour.  $\overline{P}_i^{+1}(t)$  is bounded above by the rated capacity of the TGU as shown in Equation (6) and by the ramp-up rate (when  $U_i(t) = 1$ ) and start-up rate (when  $U_i(t) = 0$ ) in (7). Equations (8) and (9) models the unit's minimum down time and start up time constraints respectively.  $\overline{U}_i^{+1}(t)$  is a binary variable indicating the available maximum state variable of the *i*th TGU at the next hour. If a TGU is online in the current hour, i.e.,  $U_i(t) = 1$ , then  $\overline{U}_i^{+1}(t)$  can be 1. Otherwise, if  $U_i(t) = 0$ ,  $\overline{U}_i^{+1}(t)$  still can be 1 only when the minimum down time constraint is satisfied and this TGU is able to start up in an hour. When  $U_i(t) = 0$  and the minimum down time constraint is not satisfied, the binary constraint can still limit  $\overline{U}_i^{+1}(t)$  to 0.

Similarly, the downward flexibility contributed by the *i*th TGU at hour *t* can be expressed as

$$F_i^{\text{do}}(t) \le P_i(t) - P_{i,\,\mathbf{r}}^{\min} \cdot \underline{U}_i^{+1}(t)$$
(10)

$$F_t^{\text{do}}(t) \le RD_i \cdot \underline{U}_i^{+1}(t) + SD_i \times \left[ U_i(t) - \underline{U}_i^{+1}(t) \right] + P_{i, \mathbf{r}}^{\min} \times \left[ 1 - U_i(t) \right]$$
(11)

$$\sum_{n=0}^{T_{i,on}^{\min}-1} U_i(t-n) \ge T_{i,on}^{\min} \times \left[ U_i(t) - \underline{U}_i^{+1}(t) \right]$$
(12)

where  $\underline{U}_{i}^{+1}(t)$  is the available minimum state variable of the *i*th TGU at the next hour.

#### 2.2.2. ESS Flexibility Contribution

Characteristics of electric energy storage and delivery make an ESS respond to changes in wind generation rapidly. Suppose that the ESS is required to maintain the charging (discharging) state for at least one hour. The flexibility contributed by the ESS can be mathematically described as,

$$F_{\text{ESS}}^{\text{up}}(t) \le P_{\text{ESS}} + P_{\text{ch}}(t) - P_{\text{d}}(t)$$
(13)

$$F_{\text{ESS}}^{\text{up}}(t) \le \eta_{d} (E_{\text{ESS}}(t) - E_{\text{ESS}}^{\text{min}}) / \Delta t + P_{\text{ch}}(t) - P_{d}(t)$$
(14)

$$F_{\text{ESS}}^{\text{do}}(t) \le P_{\text{ESS}} + P_{\text{d}}(t) - P_{\text{ch}}(t)$$
(15)

$$F_{\text{ESS}}^{\text{do}}(t) \le \left[E_{\text{ESS}}^{\max} - E_{\text{ESS}}(t)\right] / (\eta_{\text{ch}} \cdot \Delta t) + P_{\text{d}}(t) - P_{\text{ch}}(t)$$
(16)

## 2.2.3. Calculation of Operation Flexibility Metrics

The total system flexibility resources can be calculated according to the contribution of TGUs and ESS. The upward and downward flexibility metrics of system are calculated by Equations (17) and (18) respectively.

$$F_{\text{sys}}^{\text{up}}(t) = \sum_{i \in G_{Ther}} F_i^{up}(t) + F_{ESS}^{\text{up}}(t)$$
(17)

$$F_{\text{sys}}^{\text{do}}(t) = \sum_{i \in G_{Ther}} F_i^{do}(t) + F_{ESS}^{\text{do}}(t)$$
(18)

Therefore, the system flexibility metrics can be determined according their definitions.

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#### 3. BWTSGS Planning Formulation

In bundled generation systems, the matched TGUs may have difficulty following the volatile wind power. Thus, more TGUs would be required, and the operation cost and planning cost increase dramatically. ESS can store and release electric energy quickly when needed. The integration of an ESS into the bundled generation system may alleviate the operation difficulty encountered by TGUs [17] and enable efficient bundled delivery. The high share of wind power in a BWTSGS increases the variability and uncertainty in a power grid. Unlike traditional power system, volatile wind power makes the system operators deal with the high magnitudes and rates of variability in a short available lead time. Therefore, system operation flexibility is becoming a useful tool for the accurate planning of a BWTSGS. Moreover, considerations of system operation flexibility in the planning of BWTSGS can improve the operation security when facing high variability and uncertainty.

In this paper, an optimal planning model for BWTSGS considering the operation flexibility constraints is proposed to find the optimal configuration of the ESS and TGUs to alleviate the operation difficulty. The proposed planning model is shown in Figure 3. It contains two sub-models. One is the daily scheduling simulation model, and the other is the optimal planning model. The former considers the sequential operation characteristics of a BWTSGS and the system operation flexibility constraints in order to calculate the operation cost. The system operation flexibility constraints are devised in the daily scheduling simulation model to guarantee the optimal operation. The flexibility constraints are built from a probabilistic viewpoint, and fully consider the volatility and uncertainty of wind power. Moreover, the flexibility by operational state transition offers great benefits for TGUs to cope with frequent start-ups and shut-downs.



Figure 3. The proposed optimal planning model for a BWTSGS.

Figure 3 also shows that the proposed planning model generates candidate planning schemes and determines the planning scheme that minimizes the total cost of a BWTSGS. The planning scheme contains the power and energy rating of an ESS, as well as the number of TGUs for each candidate type. The candidate schemes are evaluated by the daily scheduling simulation model in order to obtain the operation cost. A wind power sequential clustering technique based on DFT is developed to improve the computation efficiency, since the computational cost for calculating the whole year's operation costs is extremely high

## 4. Daily Scheduling Simulation Model Considering Operation Flexibility Constraints

Due to the complicated operation characteristics of wind power and ESS, it is necessary to evaluate the sequential operation of wind power and ESS in the optimal planning model for BWTSGS [17]. A daily scheduling simulation model considering the operation flexibility constraints is proposed to calculate the operation cost of a BWTSGS. To reduce the computation cost, the simulation model is formulated as a mixed integer linear programming (MILP) problem.

#### 4.1. Objective Function

The scheduling simulation model intends to determine the on/off status, the output of TGUs, and the charge or discharge power of ESS to minimize the operation cost of BWTSGS. The operation cost includes the operation cost of TGUs and ESS, the environmental pollutant cost as well as the financial penalty for wind power curtailment. The objective function can be expressed as

$$\min F = \sum_{t=1}^{T} \left\{ \sum_{i \in G_{Ther}} \left[ F_i(P_i(t)) + E_i(P_i(t)) + C_i^{SU}(t) + C_i^{SD}(t) \right] + C_{O, ESS} P_d(t) + C_{CW} P_{CW}(t) \Delta t \right\}.$$
 (19)

where *F* denotes the total operation cost in a day.  $F_i(\cdot)$  and  $E_i(\cdot)$  are the production cost and the environmental pollutant cost function of the *i*th TGU. Both costs depend on the power output  $P_i(t)$ .  $C_i^{SU}(t)$  is the startup cost and  $C_i^{SD}(t)$  the shutdown cost of the *i*th TGU at hour *t*.  $C_{O, ESS}$  is the operation cost of the ESS (\$/MWh) and  $P_d(t)$  is the discharging power of the ESS at hour *t*. ESS operation cost is related to the discharging energy [17]. The product  $C_{CW} \cdot P_{CW}(t) \cdot \Delta t$  represents the financial penalty for wind power curtailment.

The operation cost of TGUs includes the production, startup, and shutdown costs, which are usually expressed as nonlinear (quadratic or exponential) functions. According to [21], all these cost functions can be approximated by a series of piecewise linear functions. Enough segments can express the original functions accurately.

The emission of  $NO_x$ ,  $CO_2$ , CO and  $SO_2$  should be restricted in electric power production. Their environmental pollutant costs are modeled by linear function of TGU power output [22],

$$E_i(P_i(t)) = \sum_{k=1}^{NE} u_k \varepsilon_{k,i} P_i(t) \Delta t$$
(20)

where the emission coefficient of the *k*th gas is related to the type of TGU [22].

#### 4.2. Operation Flexibility Constraints

According to the definitions of operation flexibility metrics, the operation flexibility constraints are formulated as Equations (21) and (22) according to the target system flexibility  $\sigma$ .

$$OFIP^{up}(t) = \Pr\left\{\mathcal{P}_{W}(t+1) \le P_{W}(t) - F_{sys}^{up}(t)\right\} < \sigma$$
(21)

$$OFIP^{do}(t) = \Pr\left\{\mathcal{P}_{W}(t+1) \ge P_{W}(t) + F_{sys}^{do}(t)\right\} < \sigma$$
(22)

Constraints (21) and (22) can be transferred to a deterministic form,

$$P_{\mathrm{W}}(t) - F_{\mathrm{sys}}^{\mathrm{up}}(t) < \mathcal{F}_{\mathrm{W}}^{(t+1)}(\sigma)$$
(23)

$$P_{\rm W}(t) + F_{\rm sys}^{\rm do}(t) > \mathcal{F}_{\rm W}^{(t+1)}(1-\sigma)$$
(24)

where  $\mathcal{F}_{W}^{(t+1)}(\cdot)$  is the inverse function of wind power PDF at hour t + 1.

#### 4.3. Operation Constraints of BWTSGS

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Constraints related to the operational characteristics of a BWTSGS are expressed as

$$\sum_{\in G_{Ther}} P_i(t) - P_{ch}(t) + P_d(t) + P_W(t) = P_{Tran} + P_{WC}(t)$$
(25)

$$0 \le P_{\rm WC}(t) \le P_{\rm W}(t) \tag{26}$$

$$\begin{cases}
\sum_{i \in G_{Ther}} S_i^{up}(t) + F_{ESS}^{up}(t) \ge BSR(t) + \beta\%[P_W(t) - P_{WC}(t)] \\
\sum_{i \in G_{Ther}} S_i^{do}(t) + F_{ESS}^{up}(t) \ge \beta\%[P_W(t) - P_{WC}(t)] \\
BSR(t) \ge \alpha\%[P_{Tran} - P_W(t) + P_{WC}(t)] \\
S_i^{up}(t) \le U_i(t) \cdot P_{i,r}^{max} - P_i(t) \\
S_i^{up}(t) \le U_i(t) \cdot RU_i \\
S_i^{do}(t) \le P_i(t) - U_i(t) \cdot P_{i,r}^{min} \\
S_i^{do}(t) \le U_i(t) \cdot RD.
\end{cases}$$
(27)

Constraint (25) represents the power balance constraint and (26) the wind power curtailment limits. Although the spinning reserve has been considered in the operation flexibility constraints, the flexibility constraints focus on the system security in coping with the changes in wind power between hours. Thus, the spinning reserve constraint is modeled as Equation (27) to ensure the system security against uncertainties such as component outages and intra-hour fluctuations of wind power [23].

#### 4.4. Operation Constraints of ESS

Constraint (28) describes the operational characteristics of an ESS. The binary charging  $U_{ch}(t)$  and discharging  $U_d(t)$  variables are inserted to represent the ESS charging and discharging state. These variables cannot be 1 at the same time.

$$\begin{cases} 0 \leq U_{ch}(t) + U_{d}(t) \leq 1\\ 0 \leq P_{ch}(t) \leq U_{ch}(t) \cdot P_{ch}^{max}\\ 0 \leq P_{d}(t) \leq U_{d}(t) \cdot P_{d}^{max}\\ E_{ESS}(t) = E_{ESS}(t-1) - P_{d}(t) \cdot \Delta t / \eta_{d} + P_{ch}(t) \cdot \eta_{ch} \cdot \Delta t\\ E_{ESS}^{ESS} \leq E_{ESS}(t) \leq E_{ESS}^{max} \end{cases}$$

$$(28)$$

In addition, constraints related to the operational characteristic of TGUs are also considered yet are not given here. These constraints have been discussed in [21].

### 5. Optimal Planning for BWTSGS

For areas with rich wind resource, but far from load centers, the light load demand severely restricts the consumption level of wind power. A great amount of wind power has been wasted thereby [4]. This paper develops an optimal planning model for BWTSGS in order to deliver the large-scale wind power to load centers and boost the consumption level of wind power. The model minimizes the total cost and determines the optimal power and energy rating of an ESS and the number of TGUs for each candidate type under the assumption that the wind power farm has been built.

The proposed scheduling simulation model can calculate the operation cost of a BWTSGS, but takes unacceptable computational cost for a year's simulation. The common remedy of existing methods employs typical days to approximate the wind power sequential nature, but they overly concentrate on the wind power fluctuation and overestimate the annual production cost. In this paper, a DFT based sequential wind power clustering method is developed to calculate the production cost of a BWTSGS with a high accuracy and reasonable computation cost.

## 5.1. Objective Function

The objective function of the proposed optimal planning model for BWTSGS consists of the investment, operation, and maintenance costs of ESS and TGUs over the planning period. All of the costs are transformed to the present value considering the discount rate. Since it is assumed that the wind farm has been built, costs related to wind turbine generators (WTGs) are not considered. The objective function is expressed as

$$C_{\text{I\&O\&M}} = C_{\text{I}}(G_{\text{Ther}}, E_{\text{ESS}}, P_{\text{ESS}}) + C_{\text{O}}(G_{\text{Ther}}, E_{\text{ESS}}, P_{\text{ESS}}) + C_{\text{M}}(G_{\text{Ther}}, E_{\text{ESS}}, P_{\text{ESS}}).$$
(29)

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In addition to the initial investment cost, the total investment cost should contain the replacement cost when some facilities reach their lifetimes in that lifetimes differ among various facilities. An ESS has a shorter lifetime than a TGU. Suppose that only the ESS would reach its lifetime during the planning period which is an integer multiple of ESS lifetimes. Then, the investment cost can be expressed as

$$C_{\rm I} = \sum_{i \in G_{Ther}} CI_i + \frac{1 - (1 + r)^{-Y}}{1 - (1 + r)^{-L_{\rm ESS}}} \times (C_{\rm ESS, E}E_{\rm ESS} + C_{\rm ESS, P}P_{\rm ESS})$$
(30)

where the replacement cost of an ESS is equal to its investment cost.

The maintenance cost of TGUs could be a certain percentage of their investment cost [5]. The maintenance cost of an ESS depends on its power rating [16]. The maintenance of a BWTSGS can be expressed as

$$C_{M} = \frac{1 - (1 + r)^{-Y}}{1 - (1 + r)^{-1}} \times \left(\tau \times \sum_{i \in G_{Ther}} CI_{i} + C_{M, ESS} \cdot P_{ESS}\right).$$
(31)

Since the production costs of a BWTSGS for different years are very close, the annual operation costs over the planning period are assumed to be identical. Then the total operation cost can be expressed as:

$$C_{\rm O} = \frac{1 - (1 + r)^{-Y}}{1 - (1 + r)^{-1}} F_{\rm A}(G_{\rm Ther}, E_{\rm ESS}, P_{\rm ESS}).$$
(32)

 $F_{\rm A}$  represents the annual operation cost of a planning scheme.

#### 5.2. Constraints of Optimal Planning Model

The constraints of the proposed planning model include the TGUs' capacity constraint and wind power penetration constraint.

## 5.2.1. TGUs Capacity Constraint

The total capacity of the TGUs in a BWTSGS should satisfy the transmission power even without wind power.

$$\sum_{i \in G_{Ther}} P_{i,r}^{\max} \ge P_{\text{Tran}}$$
(33)

## 5.2.2. Wind Power Penetration Constraint

The aim of building a BWTSGS is to make full use of the wind power and reduce the emission, thus the share of wind power should be ensured.

$$\frac{P_{\mathsf{W},\mathsf{r}}}{\sum\limits_{i\in G_{Ther}} P_{i,\mathsf{r}}^{\max} + P_{\mathsf{W},\mathsf{r}}} \ge \rho,\tag{34}$$

where  $\rho$  is the minimum wind power penetration ratio.

## 5.3. Accelerating Technique

This section describes a sequential wind power clustering technique to speed up the computation process. Discrete Fourier transform (DFT) can well represent the sequential fluctuation of wind power by transforming time sequence to the frequency domain [24]. In order to reduce the computational cost and estimate the annual operation cost accurately, a DFT based sequential wind power clustering technique is developed. The main steps are given below.

i Partition the historic wind power data into diurnal wind power sequences (DWPSs). Each DWPS contains 24 sequential wind power points.

- ii Convert each DWPS into frequency domain data using DFT.
- iii Classify DWPSs into different clusters by the k-means cluster [25] method based on their spectra.
- iv Use the DWPS that is randomly selected from each cluster to represent the cluster. Calculate the annual operation cost by

$$F_{\rm A} = 365 \times \sum_{j=1}^{NC} \left[ \frac{NS_j}{NS} \times F(G_{Ther}, P_{ESS}, E_{ESS}, \mathbf{P}_j^{Rand}) \right]$$
(35)

where *NS* is the total number of recorded DWPSs, *NS<sub>j</sub>* is the DWPS number of the *j*th cluster, and *NC* is the cluster number.  $F(G_{\text{Ther}}, P_{\text{ESS}}, E_{\text{ESS}}, \mathbf{P}_{j}^{\text{Rand}})$  is the daily operation cost calculated by the scheduling simulation model with the planning schemes of  $G_{\text{Ther}}, P_{\text{ESS}}, E_{\text{ESS}}$ , and the DWPS  $\mathbf{P}_{j}^{\text{Rand}}$ .

The number of clusters impacts the accuracy and computational cost of the proposed model. More clusters imply that DWPSs in the same cluster are closer to each other. Thus, the calculated annual operation cost is more accurate, but at the expense of longer time to complete the calculation. A proper number of clusters could be selected by the elbow technique [26] using historic wind speed data. 30-year wind speed data from 1984 to 2013 collected at Valkenburg, Netherlands are adopted in the study [27].

Figure 4 shows the box plot of the percentage differences between the annual operation cost obtained with clustering and the cost obtained using the 30-year wind speed data directly. Clustering is carried out by partitioning 30-year data into 2 to 30 clusters and randomly selecting one day's DWPS in the cluster as the DWPS of that cluster. Each + denotes one of the calculated annual operation cost differences of a typical planning scheme for BWTSGS. It is observed from Figure 4 that the average difference and its deviation decrease as the number of clusters increases. When the number of clusters is 16 or higher, the average difference and deviation only decrease in a very insignificant manner. Therefore, an *NC* value equal to 16 is adopted in the case study.



Figure 4. Statistical analysis on the differences of calculated annual operation costs.

# 6. Case Studies

Several case studies have been conducted to illustrate the feasibility and effectiveness of the proposed optimal planning model for BWTSGS. All of the case studies intend to build matched facilities to make full use of wind power based on a 1000 MW wind farm. The rated capacity of WTG is 2 MW. The cut-in, the rated, and the cut-out speeds are 3.33 m/s, 8.33 m/s, and 15.28 m/s, respectively [28]. The transmission power of the bundled generation system is fixed at 2000 MW [9]. The planning period and the lifetime of the ESS are respectively 20 years and 10 years.

Four types of TGUs are chosen as the candidate units, and the parameters are shown in Table 1 [29,30]. Table 2 lists the environmental pollution cost for each greenhouse gas. The parameters of ESS based on the compressed air energy storage (CAES) case are shown in Table 3 [17,31]. Assume that in the scheduling simulation model the coefficients of basic and additional spinning reserve

requirement are 0.1 and 0.2 [9,23]. The rest parameters are set as Table 4. The statistical hourly wind speed data of the Valkenburg station from 1984 to 2013 [27] are adopted as wind speed data of the given wind farm.

		U1	U2	U3	<b>U</b> 4
$P_r^{max}$ (MW)		640	555	140	58
$P_r^{\min}$ (MW)		320	280	70	30
A (\$/h)		1300	1000	700	660
<i>B</i> (\$/MW h)		15.6	16.19	16.7	25.95
<i>C</i> (\$/MW <sup>2</sup> h)		0.00042	0.0048	0.002	0.00413
T <sub>i</sub> <sup>on</sup> (h)		8	6	5	1
$T_i^{off}(h)$		8	6	5	1
Hot start cost (\$)	)	6000	4500	550	30
Cold start cost (\$	)	12,000	9000	1100	60
Cold start hours (	h)	5	4	4	0
	NO <sub>x</sub>	3.507	3.594	3.976	4.101
Emission coefficients	CO <sub>2</sub>	805.483	810.559	832.954	840.240
(kg/MWh)	CO	0.101	0.108	0.138	0.147
-	$SO_2$	0.303	0.340	0.501	0.553

Table 1. Parameters of thermal generating units (TGUs).

Table 2. Cost coefficient of pollutant emissio
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Greenhouse Gas	$NO_x$	CO <sub>2</sub>	CO	SO <sub>2</sub>
Pollutant cost coefficients (\$/kg)	1.428	0.005	0.166	1.000

Table 3. Parameters of energy storage system.

Capital cost	Capacity cost Power cost	3000 \$/MWh 560,000 \$/MW		
O&M cost	Maintenance cost Operation cost	1200 \$/MWh/year 1.5 \$/MWh		
Efficiency	Charge Discharge	0.9 0.875		

Table 4.	Other	parameters	used in	case studie	es.

Parameters	τ	C <sub>CW</sub>	r	ρ	σ
Value	2.2%	160 \$/MWh	0.08	0.3	0.001

The bacterial foraging optimization algorithm is adopted to solve the proposed model [32]. The decision variables constitute a bacteria as  $\theta = [P_{\text{ESS}}, E_{\text{ESS}}, N_1, \dots, N_4]$ , referring to the power and energy rating of an ESS, and the number of each TGU type. MATLAB and GUROBI solver are adopted to solve the daily scheduling simulation model.

# 6.1. Case 1: Effect of Flexibility Constraints

The effect of flexibility constraints is investigated. This case study is conducted with three scenarios of a BWTGS without an ESS. The goal is to transport wind power to remote load centers by bundling delivery wind and thermal power.

## Scenario 1.1: Ignore the flexibility constraints.

Scenario 1.2: Consider the flexibility constraints but ignore the flexibility contributed by the TGUs through transitioning operating states.

Scenario 1.3: Consider the flexibility constraints and the flexibility contributed by the TGUs through transiting operating states.

Table 5 presents the results of the optimal scheme, cost, and flexibility for each scenario. Among the results of the three scenarios, the downward flexibility is much less than the upward flexibility, which is in good agreement with the results in [6]. This phenomenon indicates that deficiency of the upward flexibility resources is the leading cause limiting the integration of wind power.

Scenario		Opti Scho	imal eme		Total Cost		Costs fo	Financial Penalty	OFIPup	OLIDqo		
Stehano	U1	$(\$ \times 10^9)$ U2 U3 U4		Investment Cost ( $\$ \times 10^9$ )	Maintenance Cost ( $\$ \times 10^8$ )	Production Cost ( $\$ \times 10^9$ )	Emission Cost ( $\$ \times 10^9$ )	(\$ × 10 <sup>6</sup> )	0111	om		
Scenario 1.1	3	0	2	0	6.0102	1.3829	3.1554	2.8066	1.3770	12.823	$1.33 imes10^{-3}$	$2.11  imes 10^{-5}$
Scenario 1.2	2	1	2	3	6.1969	1.4388	3.2831	2.9194	1.3918	11.849	$5.18 imes10^{-4}$	$1.72  imes 10^{-5}$
Scenario 1.3	2	1	1	5	6.1712	1.4237	3.2487	2.9895	1.3889	4.4101	$4.39  imes 10^{-4}$	$1.52  imes 10^{-6}$

Table 5. Optimal schemes and costs on the effect of reliability constraints.

Close examination of Table 5 reveals that, due to the flexibility constraints, more TGUs are required. Thus, the total costs in scenarios 1.2 and 1.3 increase compared with that of scenario 1.1, while the flexibility metrics in scenarios 1.2 and 1.3 decrease. This phenomenon implies that the risk of coping with the variability of wind power is reduced. The results of scenario 1.2 and 1.3 indicate that considering the state transition of TGUs reduces the total cost and flexibility metrics. It is also observed from Table 5 that more U4s are installed in scenario 1.3. This shows that the proposed model is capable of considering the TGUs with different minimum on/off times. Hence, the proposed model enables an efficient configuration of different types of TGUs in the bundled generation system.

# 6.2. Case 2: Effect of ESS Integration

The benefit of integrating an ESS into bundled generation system is investigated. This case study is conducted with two scenarios. In this case study, both the flexibility constraints and the flexibility contributed through the TGU state transition are considered.

Scenario 2.1: Build a bundled wind-thermal generation system (BWTGS) without an ESS. Scenario 2.2: Build a bundled wind-thermal-storage generation system (BWTSGS).

Table 6 shows the optimal schemes and Table 7 lists the cost of each optimal scheme for both scenarios. It is observed from Table 6 that the number of U4 in scenario 2.2 is much smaller than that in scenario 2.1. But the reduction of matched TGU capacity in scenario 2.2 from scenario 2.1 is not obvious. This illustrates that an ESS can lower the demand of rapid start/shut down generators, which have higher operation costs. As a result, the operation cost of the TGU drops from \$2.9895 × 10<sup>8</sup> in scenario 2.1 to \$2.8370 × 10<sup>8</sup> in scenario 2.2. BWTSGS can lift the operation difficulty of matched TGUs in BWTGS and lower the operation cost.

Scenario	P <sub>ESS</sub> (MW)	E <sub>ESS</sub> (MWh)	U1	U2	U3	U4	TGU Capacity (MW)
Scenario 2.1	-	-	2	1	1	5	2265
Scenario 2.2	40	120	3	0	2	1	2258

Table 6. Optimal schemes on the effect of an ESS.

An ESS also greatly reduces the wind power curtailment as can be seen from the financial penalty for wind power curtailment. Table 7 shows that the financial penalty for wind power curtailment is reduced by more than 90%. The total cost decreases from  $6.1712 \times 10^9$  to  $6.0149 \times 10^9$  which is a 2.53% reduction. This indicates that the integration of an ESS with the bundled delivery of wind and thermal power is economically favorable.

			Costs fo	or TGUs			Financial		
Scenario	Total Cost ( $\$ \times 10^9$ )	Investment Cost (\$ × 10 <sup>9</sup> )	Maintenance Cost (\$ × 10 <sup>8</sup> )	Production Cost (\$ × 10 <sup>9</sup> )	Emission Cost (\$ × 10 <sup>9</sup> )	Investment Cost $(\$ \times 10^7)$	Maintenance Cost ( $\$ \times 10^6$ )	Operation Cost ( $$ \times 10^5$ )	Penalty ( $\$ \times 10^5$ )
Scenario 2.1 Scenario 2.2	6.1712 6.0149	1.4237 1.4193	3.2487 3.2386	2.9895 2.8370	1.3889 1.3852	- 3.3302	- 1.4936	- 4.7914	44.101 4.1851

Table 7. Costs regarding the effect of an ESS.

## 6.3. Case 3: Impact of Target Flexibility

This case investigates the impact of system target flexibility on the optimal planning scheme and planning costs of BWTSGS. The operation flexibility constraints of Equations (21)–(24) state that the system operation flexibility must satisfy the target flexibility at all times. Stringent flexibility (small  $\sigma$ ) could improve system operation security, but planning and operation costs would increase. The selection of proper target flexibility would benefit BWTSGS planning.

The optimal planning scheme, total cost, and financial penalty for different target flexibility values are shown in Table 8. It is observed from Table 8 that the smaller target flexibility demands larger ESS or more TGUs to satisfy the increased flexibility requirement. This leads to higher total cost. Nonetheless, the wind power curtailment is not lowered. The financial penalty for wind power curtailment with the 0.005 target flexibility is much higher than that with target flexibility of 0.01 and 0.015. This may be the case that the increased ESS or TGU capacity due to stringent flexibility is too expensive. Thus, the system curtails the wind power so as to warrant the system flexibility requirement and enhance the system operation security.

Taraat		Optir	nal Scl	heme			Tatal Cast	Financial	
Flexibility	P <sub>ESS</sub> (MW)	$\begin{array}{c} P_{\rm ESS} & E_{\rm ESS} \\ (MW) & (MWh) \end{array}  U1  U2  U3 \end{array}$		U4	$(\$ \times 10^9)$	Penalty ( $\$ \times 10^5$ )			
0.001	240	600	3	0	2	2	6.2412	0	
0.005	80	220	3	0	2	1	6.0738	30.676	
0.01	40	120	3	0	2	1	6.0149	4.1851	
0.015	70	160	3	0	2	0	6.0036	13.875	

Table 8. Results on the impact of target flexibility.

#### 6.4. Case 4: Effect of ESS Cost

The ESS cost may influence the benefit of ESS integration. Sensitivity analysis is carried out on ESS cost in this case study. The planning of BWTSGS is conducted under various ESS costs. They are 0.8, 1.0, 1.2, 1.4, and 2 times of the ESS cost considered in case 2.

Table 9 shows the optimal schemes and costs for the TGUs and ESS. The total cost of a BWTSGS increases with the increase of ESS cost. It can be seen from Table 9 that when the ESS cost is 0.8 times of that in case 2, an ESS with larger optimal energy and power rating is required, but U4 is not needed. An increase of EES capacity cuts down wind power curtailment so that the financial penalty gradually declines to zero. Nonetheless, the planning of ESS is not sensitive to the increase of ESS cost. Up to a 20% higher ESS cost does not change the optimal scheme of a BWTSGS. When the ESS cost increases by 40%, the energy rating of an ESS in the optimal scheme decrease from 120 MWh to 100 MWh, while the planning result of TGUs does not change. ESS cost higher than this level does not affect the optimal planning of ESS. It can be concluded that the cost of an ESS has only a slight impact on the benefit of building a BWTSGS.

		Optim	al Sch	eme				Total Costs for TGUs						Financial	
ESS Cost	P <sub>ESS</sub> (MW)	E <sub>ESS</sub> (WMh)	U1	U2	U3	U4	Total Cost ( $\$ \times 10^9$ )	Investment Cost (\$ × 10 <sup>9</sup> )	$\begin{array}{c} \text{Maintenance} \\ \text{Cost} \\ \textbf{(\$ \times 10^8)} \end{array}$	Production Cost ( $$ \times 10^9$ )	Emission Cost (\$ × 10 <sup>9</sup> )	Investment Cost $(\$ \times 10^7)$	Maintenance Cost (\$ × 10 <sup>6</sup> )	Operation Cost ( $$ \times 10^5$ )	Penalty $(\$ \times 10^5)$
0.8	100	220	3	0	2	0	5.9972	1.3829	3.1554	2.8337	1.3955	6.6323	2.1905	10.6871	0
1.0	40	120	3	0	2	1	6.0149	1.4193	3.2386	2.8370	1.3952	3.3302	1.4936	4.7914	4.1851
1.2	40	120	3	0	2	1	6.0219	1.4193	3.2386	2.8370	1.3952	3.9963	1.7923	5.7497	4.1851
1.4	40	100	3	0	2	1	6.0290	1.4193	3.2386	2.8382	1.3960	4.6500	1.7425	5.4048	4.2251
2.0	40	100	2	0	2	1	6.0409	1 4102	2 2296	2 0276	1 2052	6 6 4 2 0	2 4902	7 5964	4 1051

Table 9. Results on the effect of ESS cost.

## 7. Conclusions

For generation planning including large-scale wind power integration, it is essential to take the system operation flexibility into account. Firstly, this paper develops the system operation flexibility metrics for generation planning through considering the flexibility contribution of TGUs by operational state transition. Secondly, an optimal planning model for the bundled wind-thermal-storage generation system (BWTSGS) considering the operation flexibility constraints is proposed. The proposed BWTSGS planning model determines the power and energy rating of an ESS as well as the type and number of TGUs considering the sequential operation characteristics of wind power and ESS. The integration of an ESS enables the system to alleviate the challenges faced by TGUs and to reduce the operation and planning costs. A daily scheduling simulation model of BWTSGS has been developed to take into account the sequential operation characteristics of BWTSGS. The model considers the system operation flexibility constraints and the operational state transition of TGUs. A wind power sequential clustering technique based on DFT has also been presented for efficient computation of the proposed planning model.

The BWTSGS method provides an effective means of bundling the delivery of wind and thermal power for areas with abundant wind resources yet geographically far away from heavy load centers. Results from case studies have demonstrated the following:

- The integration of an ESS lessens the requirement of quick start/shut down generators so that the operation and planning costs of bundled delivery of wind and thermal power are reduced. The cost of the ESS in the proposed model is not an issue.
- 2) More TGUs are required to meet the system operation flexibility constraints. The target flexibility should be set appropriately.

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## Nomenclature

	CONSTANTS										
А,В,С	Coefficients of the quadratic production cost function of thermal generating unit (TGU)	BSR	Basic spinning reserve requirement without considering wind power penetration								
C <sub>CW</sub>	Financial penalty for wind curtailment, (\$/MWh)	$C_{\mathrm{ESS,E}}$	Energy rating cost of energy storage system (ESS) facility, (\$/MWh)								
C <sub>ESS,P</sub>	Power rating cost of ESS facility, (\$/MWh)	$C_{\rm M,ESS}$	Fixed operation and maintenance of ESS (\$/MWh/year)								
C <sub>O, ESS</sub>	Operation cost of ESS, (\$/MWh)	CI <sub>i</sub>	Investment cost of the <i>i</i> th TGU								

CONSTANTS					
$E_{\rm ESS}^{\rm max}/E_{\rm ESS}^{\rm min}$	Maximum/minimum energy state of ESS	L <sub>ESS</sub>	Lifetime of ESS facility		
NE	Number of gas types	$P_{\rm ch}^{\rm max}/P_{\rm d}^{\rm max}$	Maximum charging/discharging power of ESS		
$P_{i,r}^{\max} / P_{i,r}^{\min}$	Maximum/minimum rated power output of the <i>i</i> th TGU	P <sub>W,r</sub>	Wind power capacity		
P <sub>Tran</sub>	Transmission power of the bundled wind-thermal-storage generation system (BWTSGS)	Т	Hours considering in scheduling simulation model		
$T_{i,\text{off}}^{\min}/T_{i,\text{on}}^{\min}$	Minimum off/on time of the <i>i</i> th TGU	$T_i^{ m startup}$	Start-up time of the <i>i</i> th TGU		
Ŷ	Number of years in planning period	r	Discount rate		
<i>u<sub>k</sub></i>	Environmental pollution cost for the <i>k</i> th gas, (\$/kg)	$\Delta t$	Time duration, $\Delta t = 1$ h		
α%	Coefficient of basic spinning reserve requirement	β%	Coefficient of additional up/down spinning reserve requirement		
ε <sub>k, i</sub>	Environmental pollution of the <i>i</i> th TGU for the <i>k</i> th gas, (kg/MWh)	$\eta_{\rm ch}/\eta_{\rm d}$	Charging/discharging efficiency of ESS		
ρ	Minimum wind power penetration	σ	Target system flexibility		
τ	Ratio of maintenance cost to TGU capital cost				
		Variables			
$C_{\rm I}/C_{\rm O}/C_{\rm M}$	Invest/operation/maintenance cost of the BWTSGS over the planning period	C <sub>I&amp;O&amp;M</sub>	Total cost of the BWTSGS over the planning period		
$C_i^{\mathrm{SD}}(t)/C_i^{\mathrm{SU}}(i)$	Shut-down/start-up cost of the $i$ th TGU at hour $t$	$E_{\rm ESS}$	Energy rating of ESS		
$E_{\rm ESS}(t)$	Energy state of ESS at hour t	F	Total operation cost in a day		
$F_A$	Annual operation cost of the BWTSGS	$F_{\rm ESS}^{\rm do}(t)/F_{\rm ESS}^{\rm up}(t)$	Downward/upward flexibility contributed by ESS at hour <i>t</i>		
$F_i^{\rm do}(t)/F_i^{\rm up}(t)$	Downward/upward flexibility contributed by the <i>i</i> th TGU at hour <i>t</i>	$F_{\rm sys}^{\rm do}(t)/F_{\rm sys}^{\rm up}(t)$	Downward/upward system flexibility at hour <i>t</i>		
NC	Number of clusters	NS	Total number of recorded diurnal wind power sequences (DWPSs)		
NSj	Number of DWPS in the <i>j</i> th cluster	<i>OFIP</i> <sup>up</sup>	Upward operation flexibility insufficient probability		
OFIP <sup>do</sup>	Downward operation flexibility insufficient probability	$P_{\rm CW}(t)$	Power of wind curtailment at hour <i>t</i>		
$P_{\rm ch}(t)/P_{\rm d}(t)$	Charging/discharging power of ESS at hour <i>t</i>	P <sub>ESS</sub>	Power rating of ESS		
$P_i(t)$	Power output of the <i>i</i> th TGU at hour <i>t</i>	$\overline{P}_i^{+1}(t)$	Maximum available power output of the <i>i</i> th TGU at hour $t + 1$		
$P_{\rm W}(t)$	Wind power at hour <i>t</i>	RD <sub>i</sub> /RU <sub>i</sub>	Ramp-down/ramp-up limit for the <i>i</i> th thermal generating unit (TGU)		
$S_i^{\rm do}(t)/S_i^{\rm up}(t)$	Down/up spinning reserve contributed by the <i>i</i> th TGU	$SU_i/SD_i$	Start-up/shut-down ramp limit of the <i>i</i> th TGU		

CONSTANTS					
$U_{\rm ch}(t)$	Charging state of ESS at hour <i>t</i> (1: charging, 0: otherwise)	$U_{\rm d}(t)$	Discharging state of ESS at hour <i>t</i> (1: discharging, 0: otherwise)		
$U_i(t)$	State of the <i>i</i> th TGU at hour <i>t</i> (1: on, 0: off)	$U_i^{+1}(t) / U_i^{+1}(t)$	Available maximum/minimum state variable of the <i>i</i> th TGU at hour <i>t</i> + 1		
$\mathbf{P}_{j}^{\text{Rand}}$	DWPS selected from the <i>j</i> th cluster randomly	$\mathcal{P}_{W}(t+1)$	Random wind power at hour $t + 1$		
Sets					
G <sub>Ther</sub>	Set of the TGUs				
Functions					
$f_{\mathrm{W}}^{\mathrm{t+1}}(\cdot)$	Probability density function (PDF) of wind power at next hour	$F_i(\cdot)/E_i(\cdot)$	Production/environmental pollution cost function of the <i>i</i> th TGU		
$\mathcal{F}_{\mathrm{W}}^{(t+1)}(\cdot)$	Inverse function of wind power probability distribution at hour <i>t</i> +1				
Abbreviations					
BWTGS	Bundled wind-thermal generation system	BWTSGS	Bundled wind-thermal-storage generation system		
DFT	Discrete Fourier transform	DWPS	Diurnal wind power sequences		
ESS	Energy storage system	TGU	Thermal generating units		
PDF	Probability distribution function	WTG	Wind turbine generator		

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