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Optimal Sizing of Grid-Scaled Battery with Consideration of Battery Installation and System Power-Generation Costs

Chalermjit Klansupar and **Surachai Chaitusaney** *

Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand; k.chalermjit@gmail.com
* Correspondence: surachai.c@chula.ac.th

Abstract: Variable renewable energy (VRE) generation changes the shape of residual demand curves, contributing to the high operating costs of conventional generators. Moreover, the variable characteristics of VRE cause a mismatch between electricity demand and power generation, resulting in a greater expected energy not supplied (EENS) value. EENS involves an expected outage cost, which is one of the important components of power-generation costs. A utility-scale battery energy storage system (BESS) is popularly used to provide ancillary services to mitigate the VRE impact. The general BESS ancillary-service applications are as a spinning reserve, for regulation, and for ramping. A method to determine optimal sizing and the optimal daily-operation schedule of a grid-scale BESS (to compensate for the negative impacts of VRE in terms of operating costs, power-generation-reliability constraints, avoided expected-outage costs, and the installation cost of the BESS) is proposed in this paper. Moreover, the optimal BESS application at a specific time during the day can be selected. The method is based on a multiple-BESS-applications unit-commitment problem (MB-UC), which is solved by mixed-integer programming (MIP). The results show a different period for a BESS to operate at its best value in each application, and more benefits are found when operating the BESS in multiple applications.

Keywords: energy storage system; expected energy not supplied; mixed-integer programming; optimal sizing; optimal daily-operation schedule; power-generation cost; variable renewable energy

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1. Introduction

Electricity produced by solar and wind generation has variable characteristics because of the weather-dependent nature of the resources. Thus, these types of generation are generally referred to as variable renewable energy (VRE). The intermittency of VRE changes the shape of residual demand curves contributing to the inefficient operation of conventional generators. For example, solar is available in the daytime to serve electricity demand. Thus, conventional generators need to decrease their output. At night, solar is unavailable to serve the demand. Therefore, conventional generators need to increase their output. These operations of conventional generators require instantaneous ramping and frequent start-ups and shutdowns, which lead to high operating-generation costs during the day [1]. Moreover, VRE poses negative impacts to power systems' reliability in many countries, including Thailand, because it contributes to a mismatch between electricity demand and power generation [2–4]. The increased mismatch will result in a greater value of expected energy not supplied (EENS), which increases the possibility of power outages. EENS involves the expected outage cost, which is one of the important components of power-generation costs [5].

Energy storage systems involving compressed air, flywheels, pumps, and battery technologies are used to solve VRE impacts. Battery energy storage systems (BESSs) represent the most interesting energy storage technology for relieving the impact of VRE because of their fast response characteristics [6], and the installation costs are continuously decreasing [7]. A behind-the-meter (BTM) BESS installed on site with VRE generators is primarily aimed to benefit customers through electricity bill savings and demand side management [8]. A utility-scale BESS is most often used to maintain the reliable operation of a power system (ancillary services) and mitigate the VRE impact [9]. Utility-scale BESS projects are planned in many countries. For example, in the United States, 3616 MW of new utility-scale BESS capacity is planned during 2020–2023, and the total installed capacity is expected to increase to 17 GW by 2050 [10]. To provide ancillary services, BESS is used to operate in different applications, such as spinning-reserve, ramp-rate, firm-capacity, and frequency-regulation services [11,12]. However, overinvestment in BESS probably leads to high system costs that burden customers [13]. Therefore, a method to determine the optimal sizing and daily-operation schedule of a grid-scale BESS is needed. The method needs to be able to minimize the operating costs of the system, the avoided expected outage cost of the system, and the installation cost of BESS, while satisfying the power-generation-reliability constants. Additionally, the method needs to be able to select the appropriate BESS application to operate in the most cost-effective way.

In general, the methods to determine the optimal sizing and operation schedule of grid-scale energy storage are illustrated by the unit commitment problem (UCP) [14]. Several authors [15–22] have proposed UCP methods to determine the optimal daily-operation schedules of the grid-scale energy storage system, while considering the power system's reliability. Other researchers [15–17] have focused on the use of energy storage to accommodate an imbalance between the power supply and the power demand (regulation). Still others [18–20] have used energy storage to establish the operating reserve. In two articles [21,22], energy storage was used in two applications [21] focused on regulation and administration, while another author [22] focused on regulation and the operation reserve. However, optimizing the installation size of a grid scale energy storage system was not mentioned in these articles.

Many researchers have presented guidelines to define both the size and the optimal daily operating schedule of energy storage systems. Other authors [23–25] have provided methods to determine the optimal sizing and the operation schedule of a grid-scale BESS and considered the operating costs and the installation cost of energy storage. Two articles [23,24] were focused on shifting the VRE generation ability to coincide with peak demand (firm capacity). Another [25] was focused on purchasing inexpensive energy, which is available during periods when system marginal prices are low, to charge the storage system. Stored energy can then be discharged to be used or sold later when the prices are high during peak hours (arbitrage). However, some researchers [23–25] have neglected the power-generation-reliability constraint, which is an important variable that is affected by VRE, such as EENS. Other authors [26] have considered the power-system-reliability constraints but neglected the cost effectiveness of BESS installations. In terms of sizing, the researchers basically determined the energy storage size from the reserve amount required by the power system. Nevertheless, trading off between the daily operating costs, the power-generation-reliability constants, the avoided expected-outage cost, and the installation cost of grid-scale energy storage were not mentioned in [23–26].

Some articles [27–29] have presented methods to find the optimal sizing and optimal daily-operation schedule of grid-scale energy storage, considering both cost effectiveness and the power-generation-reliability constraints, such as EENS, the system average interruption duration index (SAIDI), the system average interruption frequency index (SAIFI), and the loss-of-load probability (LOLP). However, in [25], the focus was on energy arbitrage using compressed air energy storage systems, which are less suitable than BESS in Thailand [2]. In [26], the focus was on the impacts of VRE on transmission systems rather than generation systems. In [29], the focus was on distributed-power systems, not utility-scale systems. Importantly, the frequently used BESS applications are reserve, regulation, and ramping [30]. If a single energy storage system can be used for multiple applications, it would probably be more cost-effective [31]. However, the existing studies [15,28,29] have focused on specific applications of energy storage.

Many articles also support the idea that a single battery should provide multiple applications. These articles explicitly analyzed energy storage applications. The authors of [32] stated that energy storage can generate much more value when multiple, stacked services are provided by the same device or fleet of devices. The author [33] gave a general overview of the BESS applications that have demonstrated a high potential in the past few years and also described revenue-stacking possibilities. The article [34] analyzed the techno-economic performance of single-use and multi-use operation strategies on a stationary lithium-ion BESS serving a characteristic commercial consumer in Germany. The results show that the stationary BESS is highly profitable under a dynamic multi-use operation strategy.

Based on the literature review, the previous studies have mainly focused on finding energy storage operation schedules and considering minimizing energy storage operation costs and system-reliability constraints. Many of them have included energy storage sizing and installation costs as considerations, while a few studies have included multi-applications into their methods. However, none of them have considered all the mentioned issues in a single study. Table 1 shows the research gaps in the existing studies compared to the proposed method.

Table 1. The research gaps compared to the proposed method.

Reference	ESS Operation Schedule	Multi-Application Used	ESS Sizing	ESS Operation Cost	ESS Installation Cost	Reliability Constraints
[15]	✓			✓		✓
[16]	✓			✓		✓
[17]	✓			✓		✓
[18]	✓			✓		✓
[19]	✓			✓		✓
[20]	✓			✓		✓
[21]	✓	✓		✓		✓
[22]	✓	✓		✓		✓
[23]	✓		✓	✓	✓	
[24]	✓		✓	✓	✓	
[25]	✓		✓	✓	✓	
[26]	✓		✓	✓		✓
[27]	✓		✓	✓	✓	✓
[28]	✓		✓	✓	✓	✓
[29]	✓		✓	✓	✓	✓
proposed	✓	✓	✓	✓	✓	✓

This paper proposed a method to determine optimal sizing and daily-operation schedules of a grid-scale BESS to compensate for the negative impacts of VRE using the UCP and economic-dispatch-based model. The main contributions of this paper can be summarized as follows:

1. The BESS optimal size and daily schedule are determined considering operating costs, power-generation-reliability constraints, avoided expected-outage costs, and the installation costs of BESS. These considerations make the method comprehensive and fill the research gaps in the existing studies.
2. The optimal BESS application at a specific time during the day can be selected among reserve, regulation, and ramping, making the operation of BESS more cost effective.
3. The results from a proposed method were compared with the existing method and applied to different scenarios.

The method assumed electrical systems with a centralized structure, and the BESS was considered as one of the utility assets. The multiple BESS applications unit commitment (MB-UC) was solved by mixed-integer programming (MIP). The test system is Thailand's power-generation system. This paper is applicable to policymakers interested in effectively integrating a grid-scale BESS into their power system.

The remainder of the paper offers the following: Sections 2 and 3 present background knowledge on EENS, the general grid services of BESS, and battery energy storage system characteristics. Problem formulation is provided in Section 4. Thailand's power-generation-system model is described in Section 5. Simulation scenarios are presented in Section 6. The results and discussion are in Section 7. The conclusion is in Section 8, followed by the reference section.

2. Expected Energy Not Supplied

Due to VRE's continued cost reductions and environmental protection pressures, many countries/regions are planning to integrate high wind and PV penetration levels. Unlike most power plants, the power generation of VRE cannot be controlled by changing the amount of fuel burned or the water flow rate. The power generation of VRE is dependent on weather conditions, both sunlight and wind, which are unstable, so having more VRE systems contributing to the grid will provide the overall power-generation system with more "intermittency".

Since VRE has become a greater part of power-generation systems, power plants that are able to provide reserve capacity (e.g., a dispatchable power plant) are probably less committed to the power-generation system [35]. This contrasts with the increased requirement for reserve capacity due to fluctuations in renewable energy, contributing to difficulties in maintaining system-operation constraints. Thus, VRE penetration affects power-system reliability.

In September 2016, a windstorm caused power outages across South Australia for hours to days. After that incident, researchers stated that such incidents could be avoided if the power system did not use so much VRE. In particular, researchers found that the incident was caused by wind-power outages. Even in extreme cold climates, coal-fired power plants and natural-gas pipelines utilize deicing technology, and these fossil-fuel power plants can still operate within normal ranges [36].

EENS is usually used as an index to illustrate power-system reliability [37]. This index depends on the total failures probability of all generators in the system, which can be calculated using the capacity-outage probability table (COPT). If EENS is high, the system has a high probability that total power generation cannot support the electricity demand, which leads to poor system reliability. EENS is used in the calculation of expected-outage costs by multiplying it with the value of lost load (VOLL), which refers to the costs of energy not supplied, as shown in the following equation:

$$C_{outage} = \text{EENS} \times \text{VOLL} \tag{1}$$

VOLL is the cost of energy not supplied and should reflect the real cost of outages for system users; it is determined by the average consumer loss to insufficient power capacity, or the value the customer wishes to be paid to avoid a peak load. VOLL varies significantly depending on geographic factors, differences in the nature of load compositions, the type of consumers that are affected and their level of dependency on electricity, differences in reliability standards, the time of year, and the duration of outages [38]. VOLL is normally high [39] because it reflects the opportunity costs of customers when electrical capacity is deficient. Thus, system operators should allocate adequate reserve capacity to support EENS to avoid the high expected-outage costs. However, the reserve capacity requirement contributes to higher overall generator operating costs.

3. Battery Energy Storage Systems

Energy storage technologies, such as compressed air, flywheels, pumps, and BESS, are used to solve VRE impacts by operating as reserve, ramp-rate, firm-capacity, and frequency-regulation services [10,11]. Among all the types of energy storage, BESS is the most effective energy storage technology for relieving the impact of VRE because of its fast-response characteristics [5] and its ability to generate reserve capacity without the minimum-generation-limit problem. Moreover, BESS installation costs have been decreasing [6]. Therefore, many countries have used batteries to support power-system reliability and stability [5,8,10,11].

3.1. General Grid Services of Bess

BESS has the potential to provide services that can ensure the reliability and stability of power systems. Figure 1 illustrates an overview of the energy storage system's application. In 2016, according to [10], The USA utility-scale battery storage was the most deployed type of system for operating reserve and ancillary services, such as frequency response and regulation with 550 MWh of installed capacity. Only 110 MWh were used for other purposes, such as arbitrage, RE curtailment, and load leveling. Furthermore, another article [5] suggested that the global trend is to install energy storage technology on power systems for ancillary services rather than for other applications, such as energy shifting and peaking capacity. Among all the types of ancillary services, there are three that are the most popular for battery use.

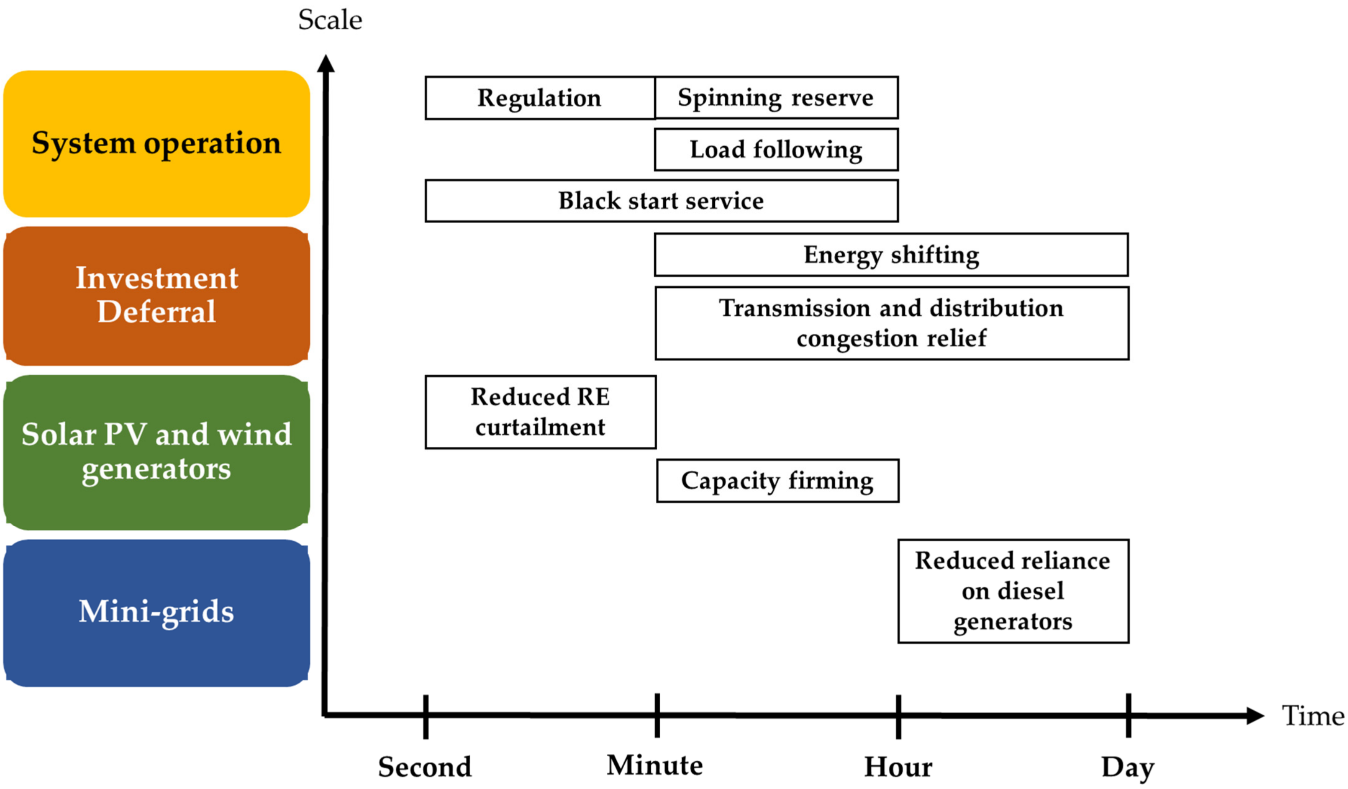

Figure 1. Applications of energy storage system.

3.1.1. Operating Reserves

The operation of generation systems requires a reserve capacity that can be called on when some portion of the normal electric-supply resources unexpectedly become unavailable. The various categories of operating reserves include spinning, non-spinning, and supplemental reserves that function on different time scales, all of which are needed to ensure grid reliability [11,12].

3.1.2. Load Following/Ramping Up of Renewables

Load following is characterized by a power output that generally changes as often as every several minutes. When solar photovoltaic (PV) penetration starts to increase, the shape of the load curve changes dramatically into the so-called solar duck curve. In large-scale battery storage systems, centralized batteries are deployed to store the surplus energy generated [9,12].

3.1.3. Regulation

Regulation is one of the ancillary services for which energy storage is especially well suited. An imbalance between the power supply and the power demand can lead to a dip or a rise in grid frequency beyond the specified limits. BESS is designed to immediately charge excess power from the grid or to discharge the necessary power to the grid to maintain a stabilized system frequency [9,12].

3.2. Battery Energy Storage System Characteristics

In designing BESS, installation costs must be considered, so the characteristics of the system significantly affect the installation costs. The considerations include whether the power system requires a BESS application that is able to serve a large amount of energy in a short period of time, or whether the system operator should design a system with a large installation capacity and slow energy service or small installation capacity and fast energy service.

This section provides information about the important BESS design characteristics. In general, the characteristics consist of seven parameters.

3.2.1. Rated Power Capacity or Available Power

Rated power capacity or available power is the parameter that indicates the total maximum power that can be discharged from the energy storage system. The parameter is presented in kilowatts (kW) or megawatts (MW) [11,12,40].

3.2.2. Energy Capacity or Storage Capacity

Energy capacity or storage capacity is the maximum amount of energy that can be stored. The parameter is presented in kilowatt-hours (kWh) or megawatt-hours (MWh) and is sized according to the power storage capacity (in MWh). However, it does not mean that all the energy in the energy storage system can be discharged. The depth of the discharge limits the discharged energy. For example, if the depth of discharge is 80%, it means that only 80% of the total installed energy storage capacity can be discharged. For any application, the required energy storage capacity is reduced by increasing the depth of discharge. For instance, if 100 MWh of energy is needed. It requires 200 MWh of BESS with 50% depth of discharge or 100 MWh of BESS with 100% depth of discharge. However, the high depth of discharge will result in a shorter battery cycle life [11,12,40].

3.2.3. State of Charge

State of charge, expressed as a percentage, represents the battery's present level of charge, which ranges from completely discharged to fully charged. The state of charge influences a battery's ability to provide energy or ancillary services to the grid at any given time [11].

3.2.4. Storage Duration

Storage duration is the amount of time a storage system can discharge energy at its power capacity before depleting its energy capacity. Storage durations relate to the C-rate or the autonomy of BESS, which is the ratio between the energy capacity (restorable energy) and maximum discharge power. For example, a battery with 1 MW of power capacity and 4 MWh of usable energy capacity will have a storage duration of 4 h. The C-rate or autonomy of a system depends on the type of storage and the type of application [11,40].

3.2.5. Cycle Life/Lifetime/Durability

Cycle life/lifetime/durability is the amount of time or cycles a BESS application can provide regular charging and discharging before failure or significant degradation. The lifetime of system depends on many factors, including charge and discharge cycling, depth of discharge, and environmental conditions. The parameter is expressed as the maximum number of cycles N (one cycle corresponds to one charge and one discharge) [11,12,40].

3.2.6. Self-Discharge

Self-discharge occurs when the energy of the battery is reduced through internal chemical reactions or when the portion of the energy that was initially stored has dissipated over a given amount of non-use time [11,40].

3.2.7. Round-Trip Efficiency

Round-trip efficiency, measured as a percentage, is the ratio between released energy and stored energy. Round-trip efficiency considers the energy losses from the power conversions associated with operating the energy storage system [11,12,40].

4. Problem Formulation

High VRE penetration changes the shape of residual demand curves. The operations of conventional generators require fast ramping and frequent start-ups and shutdowns, leading to increased operating costs of generators during the day. A grid-scale BESS mitigates the negative impacts on a power system's reliability in different applications, such as spinning reserve, ramp-rate, firm-capacity, and frequency-regulation services. This section describes the proposed mathematical model to solve the problem. The method is designed to determine optimal sizing and the optimal daily-operation schedule of a grid-scale BESS to compensate for the negative impacts of VRE. The method can be used to select the BESS application that can operate most cost effectively in a given scenario. The method minimizes power-generation-system costs, BESS operation and installation costs, and the cost of EENs. A MB-UC-based approach is used to find the BESS's optimal size and operation schedule. The MB-UC is solved by using mixed-integer linear programming.

This paper uses a BESS model to provide three main applications: as a spinning reserve, for load following/ramping up of VRE, and for regulation. A BESS is operated as one of the three applications in a considered period. Each application is designed to be used within different time frames; for example, load following/ramping up is usually planned a day ahead, regulation is planned intra-day, and as a spinning reserve is planned throughout the day regardless of the time frame [41,42]. The limitation of the BESS model is defined with the following assumptions:

(1) There is no BESS ramp-rate limitation. For example, a BESS can instantly discharge from not producing power to maximum power.
(2) A BESS has losses from the associated power conversions. This method considered only losses that occur from the round-trip efficiency.
(3) The operation cost of a BESS in this method included the charged-energy cost and the degradation cost of a BESS.
(4) The installation cost of a BESS in this method included the power-installation cost and the rated energy-installation cost.
(5) The method assumed electrical systems with a centralized structure, so a BESS was considered a utility asset.

Thus, the method is divided into two stages differentiated by the considered time frame. The first stage is day-ahead unit commitment. This stage intends to convey the commitment start-up or shutdown status of generators on the considered day with a time resolution of 1 h. The second stage is intra-day economic dispatch, considering the day-ahead unit commitment decisions from the first stage. Detailed explanations of the two stages are provided in the following subsections.

4.1. First-Stage: Unit Commitment Problem

The objective function of the first stage is to find the optimal daily schedule of generators, the optimal size, and the operation schedule of a BESS. The objective function considers BESS operating costs, power-generation-reliability constants, and BESS installation costs. The objective function is shown as Equation (2).

$$Min \sum_{t=1}^{24}\left[\sum_{k=1}^{n}(u_{k,t}(C_{k,t}P_{k,t})+u_{k,t}S_{k,t}\right]+C_{BESS,power,daily}\mathrm{BESS}_{installation,power}+C_{BESS,energy,daily}\mathrm{BESS}_{installation,energy} \quad (2)$$

where

$u_{k,t}$ is the status of power plant k (0 or 1);
$C_{k,t}$ is the fuel cost of power plant k ($/kWh);
$P_{k,t}$ is the output of power plant k (kW);
$S_{k,t}$ is the start-up cost of power plant k ($);
$C_{outage,t}$ is the expected outage cost ($/kWh);
$C_{BESS,power,daily}$ is BESS power-installation daily cost ($/kW);
$C_{BESS,energy,daily}$ is BESS energy-installation daily cost ($/kWh);
$\mathrm{BESS}_{installation,power}$ is BESS installation power (kW);
$\mathrm{BESS}_{installation,energy}$ is BESS installation energy (kWh).

The UPC is solved by considering the generator limit, the power system, and the BESS constraints as follows:

4.1.1. Generator-Limit Constraints

As mentioned in the previous sections, VRE integration requires more power-system flexibility. Conventional generators (i.e., thermal generators) provide flexibility because they have considerable mechanical inertia. However, conventional generation is limited in terms of power-system flexibility, depending on the power plants' configuration. This paper is focused on three main factors: rated power capacity (maximum power and the minimum power limit), ramp rate, and minimum up/downtime.

Rated Power Capacity or Available Power Constraints

The maximum power limit ($P_{\max,k}$) is the amount of power that a generator can produce when running at full capacity. The minimum power limit ($P_{\min,k}$) is the minimum amount of power that a generator must supply if it is committed. The boiler thermal components are stabilized at the minimum design-operating temperature. $P_{\max,k}$ and $P_{\min,k}$ are typically measured in megawatts (MW). The rated power-capacity constraints are shown in Equation (3):

$$P_{\min,k} \le u_{k,t}P_{k,t} \le P_{\max,k} \quad (3)$$

Ramp-Rate Constraints

Ramp-rate constraints are the limitations of changing the power output of a generator within the considered periods. Ramp-rate constraints can be separated into three conditions. The first one is when generator k is in a start-up state, where the ramp rate of generator k must be less than $RR_{startup,k}$. The second condition is when the generator is in a shutdown state, where the ramp rate of generator k must be less than $RR_{shutdown,k}$. The last condition is when generator k is in an operating state (not in a start-up or a shutdown state), where the RR of generator k must be less than $RR_{up,k}$ and $RR_{down,k}$. Note that ramp rates are constants, depending on the configuration of the generator.

$$\left|P_{k,t}-P_{k,t-1}\right| \le \begin{cases} RR_{startup,k} & \text{if } t>\tau \text{ and } u_{k,t}-u_{k,t-\tau}=1 \\ RR_{shutdown,k} & \text{if } t>\tau \text{ and } u_{k,t}-u_{k,t-\tau}=-1 \\ RR_{up,k}, RR_{down,k} & \text{if } u_{k,t}-u_{k,t-\tau}=0 \end{cases} \quad (4)$$

Minimum Uptime and Downtime Constraints

In general, conventional power plants are unable to start up or shut down within frequent intervals. Minimum uptime is the minimum operating time before the generator is able to shut down. Minimum down time is the minimum shutdown time before the generator is able to start up. The constraints are illustrated in Equation (5).

$$u_{k,t} \neq \begin{cases} 1 & \text{if } u_{k,t-1} = 0 \text{ and } \sum_{t-downtime}^{t-1} u_k \leq 0 \\ 0 & \text{if } u_{k,t-1} = 1 \text{ and } \sum_{t-uptime}^{t-1} u_k \leq uptime \end{cases} \tag{5}$$

In Equation (5), minimum uptime and downtime constraints are used to limit changes in a power plant's status. If power plant k is running for a period that is less than the minimum uptime, then u_k cannot be changed from 1 to 0. If power plant k has not stopped operating for a period that is greater than the minimum downtime, the u_k cannot be changed from 0 to 1.

4.1.2. Power-System Operational Constraints

A power-generation system is composed of conventional generators, VRE, energy storage, and electricity demand. All the elements have relationships with each other. In this stage, the day-ahead time frame is considered. The constraints are associated with the relationship (i.e., power balance and spinning reserve). These constraints are also considered in the second stage, except for the constraints in Equation (9).

Power-Balance Constraints

Power balance is measured in a 1 h period. The demand in each period must be equal to the scheduled conventional power generation plus the grid-scale BESS' charge/discharge power, as shown in Equation (6). A BESS can assist the generation system in responding to the demand, which corresponds to the load-following application, according to this equation.

$$P_{d,net,t} = \sum_{k=1}^{n} P_{k,t} + P_{BESS,t}. \tag{6}$$

Spinning-Reserve Constraints

In this paper, both spinning reserves from power plants and batteries are simultaneously prepared to support the fluctuation of VRE, including the possibility of a power plant failure situation.

$$SR_{k,t} = \min\left\{ (P_{\max,k,t} - P_{k,t}), \tau R_{up,k,t} \right\} \tag{7}$$

$$SR_{BESS} = \min\{ (P_{\max,BESS} - P_{BESS,t}), \tau RR_{BESS} \} \tag{8}$$

$$SR_{BESS,t} + \sum_{1}^{n} SR_{n,t} \geq SR_{Requirement} \tag{9}$$

Spinning reserve provided from a generator can be calculated from two conditions. The first condition is when the maximum power limit of a power plant minus the power generation of the plant is less than the ramp rate of the plant; the spinning reserve of a power plant is calculated by the maximum power limit of the plant minus the power generation. The second condition is when the maximum power limit of a power plant minus the power generation of the plant is more than the ramp rate of the plant; the spinning reserve of a power plant is equal to the ramp rate of the plant. The spinning reserve of BESS is calculated in the same way as generators, as shown in Equations (7) and (8), respectively. The summation of the spinning reserve provided from generators and BESS must be more than or equal to the spinning reserve requirement of the system, as shown in Equation (9). Based on this equation, BESS will be able to assist the generation system to operate as a spinning reserve.

4.1.3. BESS Constraints

The power from BESS is limited by its installed capacity, as shown in Equation (10). Thus, a BESS has more flexibility than conventional power plants. Equations (11)–(15) show the BESS operation and installation costs. In Equation (11), the BESS installation cost can be separated into two parts, consisting of the rated power installation cost and the rated energy installation cost. The rated power installation ($\text{BESS}_{installed,power}$) is the maximum power supplied by a BESS throughout the unit-commitment horizon (T), as shown in Equation (12). The rated energy installation ($\text{BESS}_{installed,energy}$) is the maximum cumulative energy charged and discharged by a BESS throughout the unit-commitment horizon (T), as shown in Equation (13). The BESS operation cost depends on BESS usage and the degradation cost, as shown in Equation (14). Equation (15) shows a method to calculate BESS usage. The degradation cost is a constant. These constraints will also be considered in the second stage.

$$-P_{\max,BESS} \leq P_{BESS,t} \leq P_{\max,BESS} \tag{10}$$

$$C_{BESS,installtion} = (\text{BESS}_{installed,power} \times C_{BESS,power}) + (\text{BESS}_{installed,energy} \times C_{BESS,energy}) \tag{11}$$

$$\text{BESS}_{installed,power} = \max\{P_{BESS,t} \quad \forall t \in T\} \tag{12}$$

$$\text{BESS}_{installed,energy} = \max\{CE_{BESS,t} \quad \forall t \in T\} \tag{13}$$

$$C_{BESS,operation} = \text{BESS}_{usage,cycle} \times \text{BESS}_{degradation,cycle} \times C_{BESS,installation} \tag{14}$$

$$\text{BESS}_{usage,cycle} = \frac{C_{BESS,operation}}{\text{BESS}_{energy,cycle}} \tag{15}$$

4.2. Second Stage: The Economic Dispatch Problem

The objective function of this stage is to minimize the generator, BESS operation, and outage costs of the system. In this stage, the intra-day economic dispatch is solved by considering the status of each generator and the BESS size, which are the day-ahead results from the first stage. This stage enables the consideration of system regulation to mitigate the uncertainty of renewable energy. The resolution time of the economic dispatch problem is 15 min. In this paper, the ability to support the electricity demand in the aforementioned resolution time is considered in the regulation application of BESS.

$$Min \quad \sum_{t=1}^{96}\left[\sum_{k=1}^{n}(u_{k,t}(C_{k,t}P_{k,t}) + u_{k,t}S_{k,t} + C_{outage,t} + C_{BESS,operation,t}\right]. \tag{16}$$

4.2.1. Uncertainty of Renewable Energy Constraints

The uncertainty of renewable energy is the error between the predicted output power and the actual output power of renewable-energy generation. In this paper, the expected power-generation profiles are set to be the average power production based on the historical statistics in 2021. The actual output-power profiles are based on the VRE-generation profile, which depends on weather conditions.

$$P_{uncertainty,t} = P_{VRE,Prediction,t} - P_{VRE,Actual,t} \tag{17}$$

4.2.2. EENS Constraints

Expected outage cost can be calculated depending on the spinning reserve, the failure-outage rate (FOR) of power plants, and VOLL. In addition, EENS is the energy that is expected to not be supplied due to power plant failures and can be calculated using the following equations.

$$C_{outage} = \text{EENS} \times \text{VOLL} \tag{18}$$

$$\text{EENS} = \sum_{e=1}^{n_e} f_e E_e \tag{19}$$

$$E_e = 0.25 \times \left[\sum_{j=1}^{m} P_{j,e} + P_{uncerainty,e} - \left(\sum_{k=1}^{n} SR_{k,e} - \sum_{j=1}^{m} SR_{j,e} \right) - SR_{BESS,e} \right] \quad (20)$$

Equation (18) shows that EENS can be calculated by the summation of energy not supplied in every situation that has the potential to cause a power outage. Equation (19) shows that the energy not supplied in each situation e can be calculated by the summation of generated power from the power plant that is unplanned shutdown in situation e, the uncertainty of VRE in situation e, and the spinning reserve remaining in the power system in situation e.

After the results of both stages are obtained, BESS installation costs, conventional generation start-up and shutdown costs (the result form the first stage), average conventional-generator-operation costs (fuel and EENS costs), and average BESS operation costs (the result from the second stage) are then combined. After that, the spinning reserve requirement is increased, before recalculating the process until the minimal total cost is found. The outcomes of the method are minimized total cost, optimal BESS size, the operation schedule of generators and BESS, and the spinning-reserve requirement. Figure 2 shows the flow chart of the proposed method. MIP is used to solve the MB-UC because it can cope with integer variables.

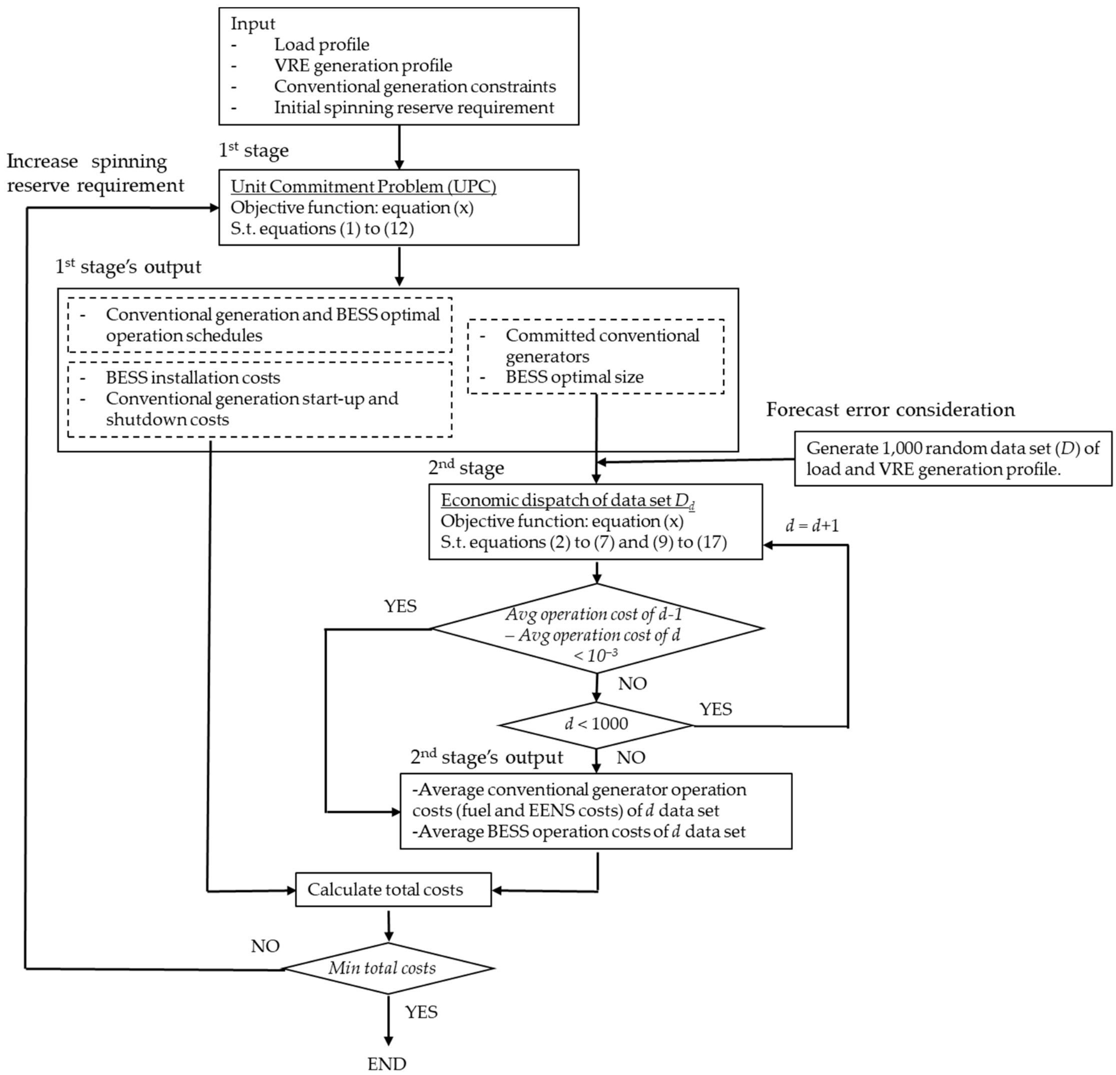

Figure 2. Flow chart of the proposed method.

5. Power-Generation-System Model

This section provides information about the data used in evaluating the BESS size, consisting of conventional power plant and electricity demand data. This paper used Thailand's power system as the test system.

5.1. Generator-Limit Constraints

This subsection addresses the Thailand power-generation system's modified data for modeling the test system and understanding the principle of the power system. The data consist of the configuration of Thailand's power system along with the generation profiles.

The number of power plants, installed capacity, variable costs, and start-up costs for each generation type, which was obtained from the conventional power plants in May 2021, according to data from the Electricity Generating Authority of Thailand (EGAT), are listed in Table 2. An example of conventional power plants is provided by EGAT and shown in Table 3. The data consist of contracted capacity, the ramp rate, the failure-outage rate, and the minimum output.

Table 2. The number and type of power plants and the power plant capacity.

Power Plant Types	Number of Power Plants	Installed Capacity (MW)	Variable Costs ($/MWh)	Start-Up Costs ($/MW$_{installed}$)
Thermal	25	8567	17.88–32.1	6.42–57.58
Combined cycle	34	20,398	34.85–54.55	6.52–95.91
Hydro	57	5105	14.48	-

Table 3. Examples of dispatchable generation technical data.

Unit No.	Contract Capacity (MW)	Min. Output (MW)	Min. Uptime (h)	Min. Downtime (h)	Failure Outage Rate	Ramp Rate (MW/15 min)
1	710	410	1	1	0.07	375
25	1436	790	3	1	0.05	915
50	1620	972	24	24	0.03	120

5.2. Electricity Demand and VRE-Generation Data

The conventional dispatchable electricity demand ($P_{dispatch,t}$) of Thailand in 2021 (net demand) can be calculated by subtracting the total electricity demand from the output power of solar generation ($P_{Solar,t}$), wind generation ($P_{Wind,t}$), and hydro-power plants ($P_{Hydro,t}$). The net demand can be calculated with Equation (21).

$$P_{dispatch,t} = P_{System,t} - P_{Solar,t} - P_{Wind,t} - P_{Hydro,t} \tag{21}$$

The VRE power-generation profile for unit commitment (each hour) in the first stage is based on the average power of each hour in 2021. The VRE-power generation profile for economic dispatch (every 15 min) in the second stage is based on a random dataset generated from actual data in 2021.

5.3. BESS Data

BESS is widely used in power systems and industries. This paper examines the use of Li-ion batteries with BESS because they have received attention from the industry due to their small size, high energy density, long life cycle, lack of memory effect, lack of pollution, low self-discharging, and high comprehensive efficiency. Additionally, the cost of Li-ion batteries continues to drop due to technology development and material innovation [43].

Li-ion batteries store 150–250 watt-hours per kilogram (kg) and can store 1.5–2 times more energy than Na–S batteries and two to three times more than redox-flow batteries. Li-ion batteries have the highest charge and discharge efficiency (about 95%), followed by lead-storage batteries (around 60–70%) and redox-flow batteries (approximately 70–75%) [12].

This paper used the estimated current costs for a 60 MW BESS with storage durations of 2, 4, 6, 8 and 10 h using thorough NREL cost models. The costs were shown in terms of energy capacity (USD/kWh) and power capacity (USD/kW) [44]. The main disadvantages of large-scale utility batteries are their short cycling times and high maintenance costs. Since a battery's lifetime depends on the discharge depth, many batteries do not completely discharge. Therefore, in this paper, it is necessary to consider the system's cost effectiveness by evaluating the characteristics and essential parameters of the battery. The BESS characteristics consist of the cycle life/lifetime/durability, the self-discharge, the round-trip efficiency, and the depth of discharge. The BESS costs and characteristics are shown in Table 4.

Table 4. Battery energy storage costs and characteristics.

BESS Characteristics	Value	Reference
Rated power capacity or available power ($/MW)	341	[44]
Energy capacity or storage capacity ($/MWh)	1365	[44]
Cycle life/lifetime/durability (cycle)	1000–10,000	[44]
Self-discharge (%/day)	0.1–0.3	[44]
Round-trip efficiency (%)	85–95	[44]
Depth of discharge (%)	75–80	[45]

6. Simulation Scenarios

This paper proposes the MB-UC method to determine the optimal size and operation schedule of BESS. The simulation scenarios are provided to show the benefit of integrating BESS. The benefit of BESS single and multi-application operations can be compared. Moreover, the cost effectiveness of BESS among different VRE penetration levels was also demonstrated. The study cases are divided into seven scenarios as follows.

Case 1: Conventional generator unit commitment (C-UC)

The scope of case 1 is as follows:

- There is no BESS installed in the power-generation system.

Case 2: Single BESS application (spinning reserve) unit commitment (SB(SR)-UC)

The scope of case 2 is as follows:

- The BESS participates in unit commitment and economic dispatch as a spinning reserve (single application).
- The BESS cannot participate in power balancing.

Case 3: Single BESS application (load following/ramping) unit commitment (SB(LF/R)-UC)

The scope of case 3 is as follows:

- The BESS participates in unit commitment and economic dispatch as load following/ramping up (single application).
- The BESS cannot participate in power balancing with a 15 min time resolution.
- The BESS is not able to provide a spinning reserve.

Case 4: Single BESS application (regulation) unit commitment (SB(REG)-UC)

The scope of case 4 is as follows:

- The BESS participates in unit commitment and economic dispatch as regulation (single application).
- The BESS cannot participate in power balancing with a 1 h time resolution.
- The BESS is not able to provide a spinning reserve.

Case 5: MB-UC

The scope of case 5 is as follows:

- The BESS participates in unit commitment and economic dispatch and can operate as a spinning reserve, for load following/ramping up, and for regulation (multi-application).

- In a considered period, the BESS is operated as the most cost effective application among the three applications.

Case 6: MB-UC (increase VRE penetration by 50%)

The scope of case 6 is as follows:

- VRE penetration in the system is increased by 50% of the existing penetration in 2021.

Case 7: MB-UC (increase VRE penetration by 100%)

The scope of case 7 is as follows:

- VRE penetration in the system is increased by 100% of the existing penetration in 2021.

7. Result and Discussion

In this section, the test results are presented and discussed. The results of this analysis combine the mathematical models discussed in Section 4 with the information already mentioned in Section 5. The study cases are divided into seven scenarios, as discussed in Section 6. Table 5 shows the summary of results.

Table 5. Summary of results.

	Case	VRE Penetration	BESS Size (MWh)	BESS Cost ($)	Average Fuel Cost ($)	Average Expected Outage Cost ($)	Start-Up/ Shutdown Cost ($)	Total Cost ($)
1	C-UC	Existing	0	0	18,658,098	135,750	84,980	18,878,828
2	SB(SR)-UC	Existing	388.81	73,974	18,653,756	98,960	50,367	18,867,057
3	SB(LF/R)-UC	Existing	0	0	-	-	-	-
4	SB(REG)-UC	Existing	37.39	7114	18,665,470	128,348	76,305	18,877,237
5	MB-UC	Existing	460.63	87,638	18,636,411	71,263	60,601	18,855,913
6	MB-UC	+50%	964.08	183,425	16,087,998	151,905	232,967	16,656,295
7	MB-UC	+100%	1494.84	284,406	14,632,552	148,647	328,734	15,394,339

From Table 5, the results of case 1 and 5 show that installing BESS with the appropriate size can decrease the total cost of the power generating system up to USD 22,915/day compared with the system without a BESS installation. BESS installation decreases the average fuel cost by USD 21,684/day, average expected outage cost by USD 64,487/day, and the start-up/shutdown cost by USD 24,379/day, respectively. In addition, as mentioned in Section 4.2, the expected outage cost of the system is also calculated in the second state. In the case of installing a BESS, the power-generation system is more flexible; therefore, the expected outage cost of the case is significantly less than the case in which a BESS is not installed. The result of case 2 shows that the total cost is less than case 1 by USD 11,771/day by using BESS as a spinning reserve. Thus, the benefit of case 5 is twice the size of that of case 2.

The result of case 3 demonstrates that Thailand's current power-generation system is not cost-effective enough to install a BESS to assist the power-generation system in load following or ramping services. Thailand's load profile is relatively stable because the hydro-power plant has the ability to improve load patterns by supplying electricity during peak period. In the case of BESS design for regulation (case 4), a BESS will operate the most during VRE power generation. Due to the large production, the actual VRE power generation deviates from the forecast, as shown in Figure 3, thus making the total cost not much different from case l.

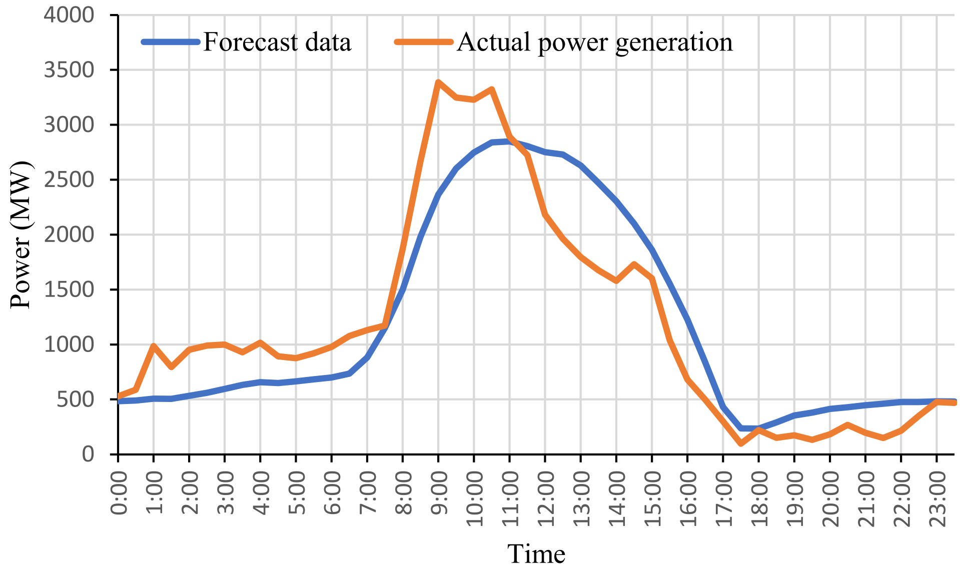

Figure 3. The actual VRE power generation compared with the forecast data.

As a result of cases 6 and 7, in which the VRE increased from 3760 MW of solar and wind power-generation systems to 5640 MW for case 6 and 7520 MW for case 7, the load would be reduced. However, even if the net load was lower than in case 5, the power plants have the ability to increase flexibility and would be running less than in case 5. The installation power of a BESS will be larger in size according to the increase in VRE.

Figures 4 and 5 illustrate how BESS applications operate in both stages. A BESS is most often operated as a spinning reserve. A BESS is operated as load following or ramping only between 18:00 p.m. and 19:00 p.m. A BESS could be operated as load following/ramping many times based on the first stage result, but when the expected outage cost is considered in the second stage, a BESS is more active as a spinning reserve. For regulation, a BESS is used all day, but it is most active between 9:00 a.m. and 15:00 a.m. That is because the power generation of the PV power-generation system was high during the period.

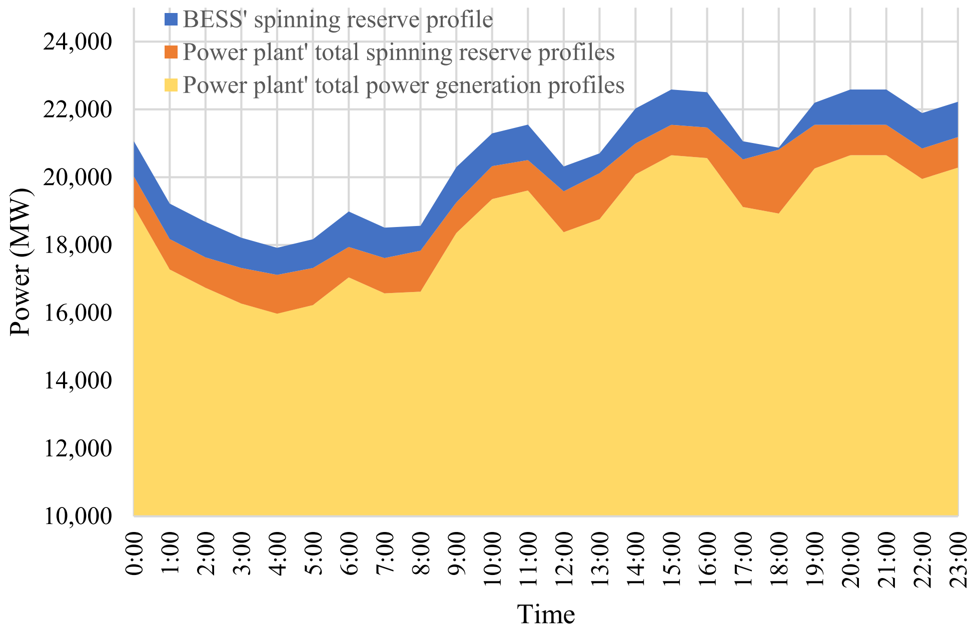

Figure 4. Power plants' total power-generation profiles, power plants' spinning-reserve profiles, and BESS spinning-reserve profiles.

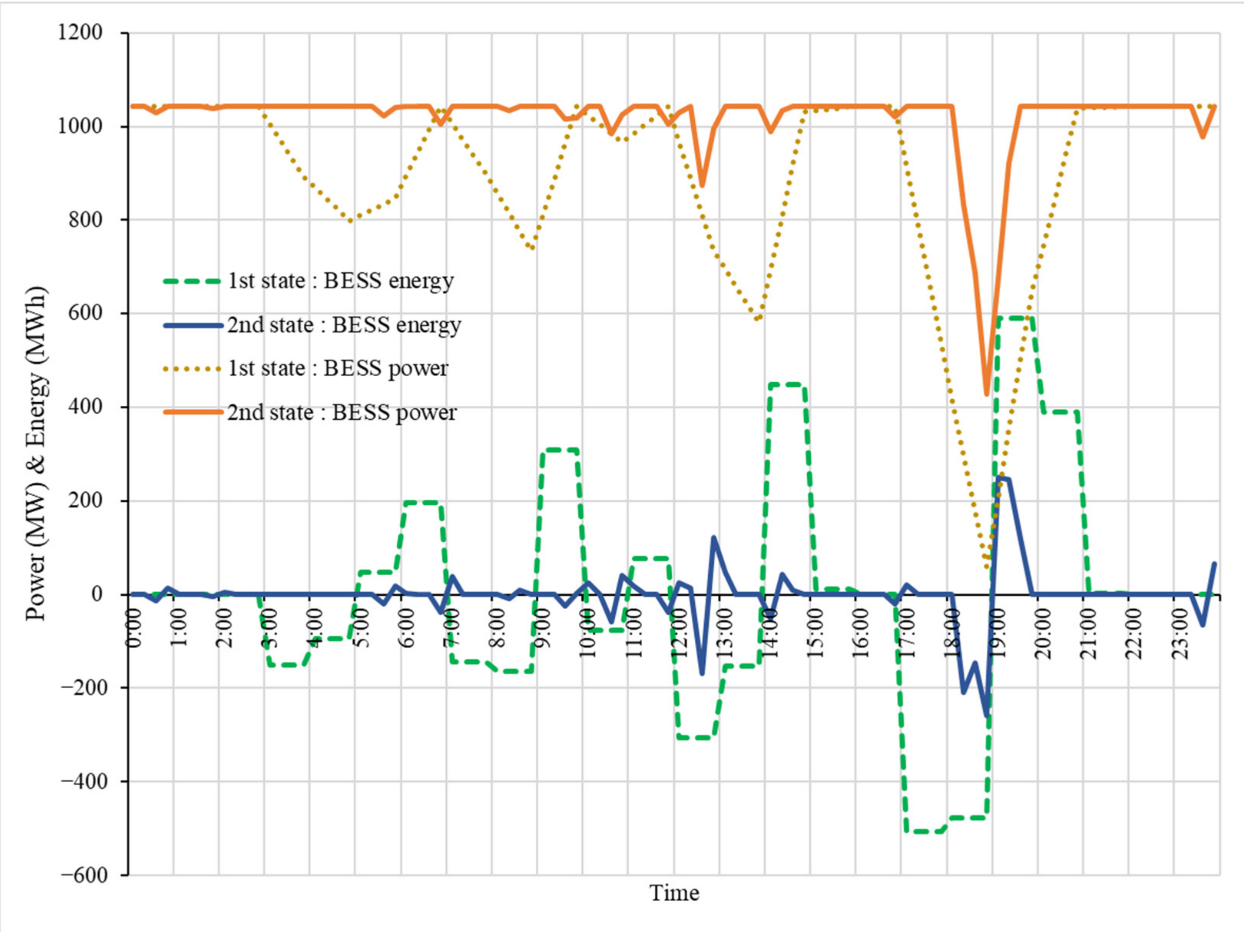

Figure 5. BESS operation schedules in first state and second state.

From the analysis of all seven cases, it is clear that a BESS has significant potential to contribute to the services of a spinning reserve and the regulation of the power-generation system. A BESS can reduce the impact of VRE on the power-generation system. In addition, using a BESS in multiple applications is more cost-effective.

8. Conclusions

High VRE penetration changes the shape of residual demand curves. The operations of conventional generators require fast ramping and frequent start-ups and shutdowns, leading to the increased operating costs of the generators during the day. In this paper, an algorithm is proposed to analyze optimal grid-scale BESS sizing and the operation schedule to support the negative impacts on power-system reliability in different applications, such as as a spinning reserve, the ramp rate, and for regulation services. The optimal size and operation schedules of a BESS installation are optimized, considering the reduced cost of expected-outage costs, start-up/shut down costs, fuel costs, and BESS installation costs. The test system is Thailand's power-generation system.

The simulation results show that a BESS operates at its best value in each case at different time points. A BESS was used for the longest period for the spinning reserve application, because when the spinning reserve was low and the load was high, EENS became high. A BESS is used to replace start-up/shutdown costs during periods of high-power ramp, but was only used in this case between 18:00 p.m. and 19:00 p.m. However, if an electrical system has high VRE penetration, usage as a ramping reserve would be more necessary, so a BESS would then be more appropriate. For the regulation application, the BESS primarily operated during a high PV power generation period (9:00 a.m.–15:00 a.m.)

to reduce the fluctuation. In the case of designing a BESS for multiple applications, the analysis shows that it is more beneficial when operating a BESS in multiple applications than in only a single application. The higher benefit of operating in multiple applications was proven from the result. This paper should be valuable for policymakers in effectively integrating a grid-scale BESS into Thailand's power system.

Future work will focus on the difference in fuel costs at each power-plant-operation point for a more accurate assessment. Further analyses of the power output of VRE generation should be carried out, depending on the forecasting technology considered. The influence of transmission and the avoided generating facilities should be considered when determining the value of a BESS.

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References

1. NREL. Power Plant Cycling Costs. 2012. Available online: https://www.nrel.gov/docs/fy12osti/55433.pdf (accessed on 17 May 2022).
2. IRENA. Renewable Energy Outlook Thailand. 2017. Available online: https://www.irena.org/publications/2017/Nov/Renewable-Energy-Outlook-Thailand (accessed on 17 May 2022).
3. Montenegro Cardona, L. Energy Flatness in the Renovation of Non-Residential Existing Buildings. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 24 June 2019.
4. Imcharoenkul, V.; Chaitusaney, S. The impact of variable renewable energy integration on total system costs and electricity generation revenue. *IEEE Access* **2022**, *10*, 50167–50182. [CrossRef]
5. Ea Energy Analyses. Renewable Energy and Reliability of Electricity Supply. 2016. Available online: https://www.ea-energianalyse.dk/wp-content/uploads/2020/02/1531_renewable_energy_and_reliability_of_electricity_supply.pdf (accessed on 17 May 2022).
6. U.S. Department of Energy. Energy Storage Grand Challenge: Energy Storage Market Report. 2020. Available online: https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Market%20Report%202020_0.pdf (accessed on 17 May 2022).
7. NREL. Cost Projections for Utility-Scale Battery Storage: 2021 Update. Available online: https://www.nrel.gov/docs/fy21osti/79236.pdf (accessed on 17 May 2022).
8. IRENA. Behind-the-Meter Batteries. 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_BTM_Batteries_2019.pdf (accessed on 17 May 2022).
9. IRENA. Utility-Scale Batteries. 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf (accessed on 17 May 2022).
10. EIA. Battery Storage in the United States: An Update on Market Trends. 2021. Available online: https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage_2021.pdf (accessed on 17 May 2022).
11. NREL. Grid-Scale Battery Storage Frequently Asked Questions. 2019. Available online: https://www.nrel.gov/docs/fy19osti/74426.pdf (accessed on 17 May 2022).
12. ADB. Handbook on Battery Energy Storage System. 2018. Available online: https://www.adb.org/sites/default/files/publication/479891/handbook-battery-energy-storage-system.pdf (accessed on 17 May 2022).
13. NREL. An Overview of Behind-Themeter Solar-Plus-Storage Regulatory Design. 2020. Available online: https://www.nrel.gov/docs/fy20osti/75283.pdf (accessed on 17 May 2022).
14. Howlader, R. Energy Storage System Analysis Review for Optimal Unit Commitment. *Energies* **2019**, *1*, 158. [CrossRef]
15. Bruninx, K. Coupling Pumped Hydro Energy Storage with Unit Commitment. *IEEE Trans. Sustain. Energy* **2016**, *7*, 786–796. [CrossRef]
16. Pozo, D.; Contreras, J.; Sauma, E. Unit Commitment with Ideal and Generic Energy Storage Units. *IEEE Trans. Power Syst.* **2014**, *29*, 2974–2984. [CrossRef]
17. Ahmadi, A.; Nezhad, A.; Hredzak, B. Security-Constrained Unit Commitment in Presence of Lithium-Ion Battery Storage Units Using Information-Gap Decision Theory. *IEEE Trans. Ind. Inform.* **2019**, *15*, 148–157. [CrossRef]

18. Li, N.; Hedman, K. Economic Assessment of Energy Storage in Systems with High Levels of Renewable Resources. *IEEE Trans. Sustain. Energy* **2015**, *6*, 1103–1111. [CrossRef]
19. Zhang, G.; Li, F.; Xie, C. Flexible Robust Risk-Constrained Unit Commitment of Power System Incorporating Large Scale Wind Generation and Energy Storage. *IEEE Access* **2020**, *8*, 209232–209241. [CrossRef]
20. Nikolaidis, P.; Chatzis, S.; Poullikkas, A. Renewable energy integration through optimal unit commitment and electricity storage in weak power networks. *Int. J. Sustain. Energy* **2018**, *38*, 398–414. [CrossRef]
21. Li, N. Flexible Operation of Batteries in Power System Scheduling with Renewable Energy. *IEEE Trans. Sustain. Energy* **2016**, *7*, 685–696. [CrossRef]
22. Wen, Y. Enhanced Security-Constrained Unit Commitment with Emerging Utility-Scale Energy Storage. *IEEE Trans. Power Syst.* **2016**, *31*, 652–662. [CrossRef]
23. Pandzic, H. Near-Optimal Method for Siting and Sizing of Distributed Storage in a Transmission Network. *IEEE Trans. Power Syst.* **2015**, *30*, 2288–2300. [CrossRef]
24. Fernandez-Blanco, R. Optimal Energy Storage Siting and Sizing: A WECC Case Study. *IEEE Trans. Sustain. Energy* **2017**, *8*, 733–743. [CrossRef]
25. Saranya, S.; Saravanan, B. Optimal size allocation of superconducting magnetic energy storage system based unit commitment. *J. Energy Storage* **2018**, *20*, 173–189.
26. Bruninx, K.; Delarue, E. Endogenous Probabilistic Reserve Sizing and Allocation in Unit Commitment Models: Cost-Effective, Reliable, and Fast. *IEEE Trans. Power Syst.* **2017**, *32*, 2593–2603. [CrossRef]
27. Echeverri Martinez, R. Optimal planning, design and operation of a regional energy mix using renewable generation. Study case: Yucatan peninsula. *Int. J. Sustain. Energy* **2020**, *40*, 283–309. [CrossRef]
28. Huang, W. Optimal Configuration Planning of Multi-Energy Systems Considering Distributed Renewable Energy. *IEEE Trans. Smart Grid* **2019**, *10*, 1452–1464. [CrossRef]
29. Liu, H. Sizing Hybrid Energy Storage Systems for Distributed Power Systems under Multi-Time Scales. *Appl. Sci.* **2018**, *8*, 1453. [CrossRef]
30. Chudy, D.; Leśniak, A. Advantages of Applying Large-Scale Energy Storage for Load-Generation Balancing. *Energies* **2021**, *14*, 3093. [CrossRef]
31. The National Rural Electric Cooperative Association; National Rural Utilities Cooperative Finance Corporation; CoBank; NRTC. Battery Energy Storage Overview. 2019. Available online: https://www.cooperative.com/programs-services/bts/documents/reports/battery-energy-storage-overview-report-update-april-2019.pdf (accessed on 17 May 2022).
32. Rocky Mountain Institute. The Economics of Battery Energy Storage 2015. Available online: https://rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStor (accessed on 17 May 2022).
33. Wüllner, J.; Reiners, N. Review of Stationary Energy Storage Systems Applications, Their Placement, and Techno-Economic Potential. *Curr. Sustain. Renew. Energy Rep.* **2021**, *8*, 263–273. [CrossRef]
34. Englberger, S.; Jossen, A.; Hesse, H. Unlocking the Potential of Battery Storage with the Dynamic Stacking of Multiple Applications. *Cell Rep. Phys. Sci.* **2020**, *1*, 11. [CrossRef]
35. IRENA. Flexibility in Conventional Power Plants. 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Flexibility_in_CPPs_2019.pdf?la=en&hash=AF60106EA083E492638D8FA9ADF7FD099259F5A1 (accessed on 17 May 2022).
36. Australian Disaster Resilience Knowledge Hub. Extreme Weather and Statewide Power Failure 2016. Available online: https://knowledge.aidr.org.au/resources/storm-extreme-weather-event-south-australia-september-2016/ (accessed on 17 May 2022).
37. Billinton, R.; Allan, R. *Reliability Evaluation of Power Systems*, 2nd ed.; Springer: New York, NY, USA, 1996; pp. 68–75.
38. ENTSO-E. 2nd ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects. 2016. Available online: https://documents.acer.europa.eu/Official_documents/Acts_of_the_Agency/Opinions/Supporting%20documents%20to%20ACER%20Opinion%20052017/Supporting%20doc_Annex%20IV_ENTSO-E_draft%20CBA%202.0.pdf (accessed on 17 May 2022).
39. Tur, M. Calculation of value of lost load with a new approach based on time and its effect on energy planning in power systems. *Int. J. Renew. Energy Res.* **2020**, *10*, 416–424.
40. Ibrahim, H.; Ilinca, A.; Perron, J. Energy storage systems—Characteristics and comparisons. *Renew. Sustain. Energy Rev.* **2008**, *12*, 1221–1250. [CrossRef]
41. Conte, F. Day-Ahead and Intra-Day Planning of Integrated BESS-PV Systems Providing Frequency Regulation. *IEEE Trans. Sustain. Energy* **2020**, *11*, 1797–1806. [CrossRef]
42. Howlader, R. Optimal Thermal Unit Commitment for Solving Duck Curve Problem by Introducing CSP, PSH and Demand Response. *IEEE Access* **2018**, *6*, 4834–4844. [CrossRef]
43. Xu, T. Considering the Life-Cycle Cost of Distributed Energy-Storage Planning in Distribution Grids. *Appl. Sci.* **2018**, *8*, 2615. [CrossRef]
44. NREL. Utility-Scale Battery Storage. 2021. Available online: https://atb.nrel.gov/electricity/2021/utility-scale_battery_storage (accessed on 17 May 2022).
45. Lachuriya, A.; Kulkarni, R. Stationary electrical energy storage technology for global energy sustainability: A review. In Proceedings of the International Conference on Nascent Technologies in Engineering (ICNTE), Vashi, India, 27–28 January 2017.