Heliyon 9 (2023) e17192

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Metropolitan water purification facilities towards variability mitigation of the renewable resources: Optimal bid method for small hydropower generators

Jae Ho Lee [a], Kyoung Hoon Kim [b], Yeon Ouk Chu [a], Jae Young Oh [a], Yong Tae Yoon [a], Sung Joong Kim [a,*]

[a] Department of Electrical and Computer Engineering, Seoul National University, Seoul 08826, Republic of Korea
[b] Korea Telecom(KT)/ 209, Jamsil-ro, Songpa-gu, Seoul, Republic of Korea

ARTICLE INFO

Keywords:
Small hydro-power generator
Metropolitan water purification facility
Renewable resources
Variability mitigation
Greenhouse gas emissions
Day-ahead and intra-day coordination

ABSTRACT

As carbon neutrality in the power system arises as one of the important issues, numerous nations have been increasing penetration of the renewable resources. However, greater penetration of the renewable resources in the power systems has caused reliability issues due to the innate unpredictable output characteristics. For minimization of unpredictability and its consequential effects on the system reliability, the nations such as the Republic of Korea, Great Britain and Australia have been introduced market-based variability mitigating measures. The incentive policy driven market-based measures were designed to draw voluntary participation from the asset owners capable of providing controllability over the resources aggregated to be a single portfolio. Small hydropower generators in metropolitan water purification facilities can be actively utilized for such mitigation because of their relatively stable output characteristics. However, entities responsible for metropolitan water purification facilities with small hydropower generators have been reluctant to participate in the market with the mitigations incentive since there are no structured methods to acquire dispatch reliability of the water resources considering participation in the energy market. Thus, this paper presents a scheduling algorithm for the aggregated portfolio of renewable resources, utilizing small hydropower generators as one of the tools for variability mitigation. In the results, the portfolio-wide forecast error was reduced to below 2% in the presence of the scheduling algorithm and small hydropower generators as mitigation resources, while the water intake schedule at water purification facilities remained evenly distributed. Small hydropower generators played a key role in mitigating variability in the algorithm, and the revenue generated from the participation of these small hydropower generators contributed to approximately one third of the gross revenue from the portfolio. The algorithm was demonstrated to provide renewable resource owners with an additional revenue stream, beyond what is typically provided by government subsidies.

1. Introduction

Decarbonisation in operations of the power system has started gaining attentions as severe changes in climate occurred in the

* Corresponding author.
E-mail address: gianthips@snu.ac.kr (S.J. Kim).

https://doi.org/10.1016/j.heliyon.2023.e17192
Received 21 November 2022; Received in revised form 7 June 2023; Accepted 9 June 2023
Available online 13 June 2023

recent years [1]. As one of the measures to minimize the emission from the conventional generation resources, the renewable resources have been introduced aggressively throughout the nations suffering from the climate change [2]. However, as penetration of the renewable resources increased in the power system, the reliability issues caused by the output variability of the renewable resources started compromising the system operations as innate consequences [3]. Thus, there have been various research efforts to mitigate the variability by the renewable resources.

The mitigation measures for the variability can be categorized by two major streams by whether introducing the physical measures or the market-based measures in the system towards the market participants with the renewable resources [4,5]. Utilization of battery energy storage system (BESS) and demand resource could be one of the mitigations measures. Beaudin. et al. [6], Jafari. et al. [7], Schill. et al. [8] and Botterud. et al. [9] asserted active utilization of BESS and their options as the system-wide mitigation measures with decarbonisation from the economic perspectives. Tang. et al. [10] and Parker. et al. [11] concluded BESS as resources providing operating reserves to be an effective mitigation measure from the operators' perspectives in consideration of the system reliability. Lee. et al. [12] and Ko. et al. [13] asserted potential technical flexibility as synergy effects through structured coordination among the decentralized resources in the power system controlling the variability locally. Wei. et al. [14] and Gong. et al. [15] suggested structured coordination of electric vehicles and demand response resources for mitigation of the variability as local measures.

In addition to the past efforts for development of the structured coordination, there have been numerous attempts to mitigate the variability by introducing advanced forecasting techniques besides utilization of BESS and demand response resources. The forecasting techniques for the photo voltaic (PV) generators consist of physical, statistical and machine learning based methods. Zhang. et al. [16] developed the forecasting model by introducing the technique combining the constraints from spatio-temporal correlations and machine learning techniques generally utilized in graphical analysis such as convolutional neural network. However, because its performance is highly dependent upon cloud movements that are virtually impossible to forecast for the next hours, there are still needs for the additional generation resources to mitigate the variability that could not be mitigated by the forecasting techniques developed. Mayer. et al. [17] also asserted the effectiveness of the forecasting method by the conventional physical method and effects on the accuracy achievement by geographical location. In statistical approach presented by Wang. et al. [18], forecasting accuracy achieved by the technique by regression was considered in the past effort. However, despite the forecasting accuracy was simulated to be improved further by the advancement, the innate error could still not be mitigated due to the error existed. Thus, the physical measures must be also accompanied. Consequently, as demonstrated in the past efforts, the physical measures could be perceived to be capable of delivering a meaningful flexibility from the perspective of the system reliability [3].

However, aside from the technical advancement, it would be infeasible from the techno-economic perspective of the market participants to adopt and develop forecasting techniques continuously to satisfy standards by the system operators. In addition, it would be difficult to draw the market participants voluntarily to aggregate additional resources with relatively stable output characteristics not willing to coordinate their outputs by financially risking themselves or research such mitigations methods without any attractive chances.

Consequently, there must be salvage opportunities after their contributions that motivate the market participants to adopt mitigation measures as the complementary policy of the physical measures. Kong. et al. [19] and Goodarzi. et al. [20] asserted introduction of incentivizing policies for mitigation of the variability caused in the power system, whereas the incentive policies thus far have been focused on the tax credits and additional complementary supports from the municipal organizations [21,22]. As the market-based measure mentioned former, the energy market requiring the participants to control the variability within the desired tolerance specified at the system operators' discretions were introduced in the nations orienting towards carbon neutral power systems such as Great Britain, India, the Republic of Korea and Australia. In the markets, the participants are tolerated to bid with the renewable energy sources aggregated up to the similar capacities of a single conventional dispatchable generation resource and eligible for the forecast incentive as long as the gross forecast error from the aggregated renewable energy sources does not vary greater than the band specified.

From the perspective of the market participants, utilization of BESS has been considered to be one possible enabler for the market-based measure. Various types of BESS have been considered to be one of the technically suitable resources for such purposes because of its control availability at operators' discretion [23]. However, due to its sizeable initial investment cost and probable risk factors, such as fire incidents, alternative resources started to be more compelling from the perspective of variability mitigation [24]. As alternative, one type of distributed energy resources (DERs) with forecastable output with carbon neutral characteristics is small hydropower generator (SHPG) [25].

SHPGs are generally installed at entrances of metropolitan water purification facilities (MWPFs), dams and control reservoirs, where sufficient potential energy from the net head for kWh generation can be acquired [26]. Meanwhile, the electricity generated can be utilized for demand curtailment of the site, participation in the energy market and trades of the greenhouse gas (GHG) emissions rights. Because the water resources must be procured day-ahead, the SHPGs can be utilized as the renewable resources with relatively stable output characteristics capable of providing the variability control in comparison to other types of DERs [27]. However, in order to schedule participation of SHPGs in the market for the variability mitigation, a new type of the scheduling algorithm must be developed because the primary utilizations purposes of the facilities where the SHPGs are installed are not to generate electricity, but to supply and procure the quality water resources for the people.

Therefore, this paper proposes a new scheduling algorithm for SHPGs at MWPF to be used as a mitigation measure against the variability caused by renewable resources in a market environment that encourages voluntary participation in variability control. In Section 2, the characteristics of SHPGs, the variability mitigation market environment, and the scheme of the scheduling algorithm are introduced. Section 3 presents the mathematical formulation of the scheduling algorithm. In Section 4, we describe the simulation environment in which the scheduling algorithm is tested. Finally, in Sections 5 and 6, the simulation results are provided to examine the effectiveness of the algorithm, and the conclusion of the paper is presented.

2. Utilization of SHPGs as variability mitigation resources

2.1. Operation process of MWPFs and characteristics of SHPGs

Primary purpose of MWPF is to provide the quality water resources processed and suitable for industrial and residential purposes after each treatment procedure [28]. A general operations flow of each MWPF can be summarized as shown in Fig. 1 below. The intake pipe is the supply pipe, where the untreated water resources are procured directly from the local basin. The bypass pipe serves as an alternative route during the intake process when the intake pipe is unavailable. The receiving well is to store the water resources transmitted through the intake pipes and to control the flow rate of the water resources to be suitable for well-specific control capability. Once the water resources from the receiving wall are distributed to the process well illustrated in the figure below, the water resources are usually treated after their purposes of utilization, whether those are for the industrial or households. Major differences between the treatment processes for the industrial and households water resources are the filtration duration and types of the filters used. In general, the duration for the households is longer to achieve greater degree of purity. After filtration process through the process well, the purified water gathers in a clear water well and dispatch pumps are activated to distribute the resources. One of the most common technical characteristics of MWPFs is the dispatch methods by natural release to minimize the electricity consumption by taking the altitude differences into account at each operations [29]. However, in the case of the MWPFs installed without sufficient differences in altitudes, dispatch pumps must be utilized for distribution of water resources.

The SHPG at MWPF generates electricity by the water resources flowing through the intake pipe as mentioned in Section 1. Majority of the SHPGs are generally recommended to be installed at the entrance of the facilities such as treatment and distribution facilities injecting treatment chemical, except for the SHPGs at dam or control reservoir not requiring the extra treatment processes for quality of water resources [30].

Major characteristics of the SHPGs installed at MWPF and dams can be categorized after the utilizations purposes as below:

1. (Operations Perspective) SHPGs at MWPF and dams are relatively can be considered to be the generation resources with significantly lower variability in comparison to the renewable resources such as WPG and PV, due to the supply-demand constraints of the water resources that must be satisfied. Further, as their operations characteristics is not different from the conventional large hydro power generator, integrating those in the current electricity grid is not technically burdening [31].
2. (Environmental Perspective) SHPGs are one of the suitable generation resources for decarbonisation that does not require any additional process installations such as sequestration devices for GHG, whereas the conventional generation resources must have additional process installations [32]. Additionally, even in the manufacturing process, SHPG does not require significant or drastic destruction of the environment from the perspective of its life cycle, whereas the life cycle of BESS is profoundly involved in environmentally hostile activities, such as environmental destruction caused by mining minerals like nickel and the recycling processes of end-of-life BESS [33].
3. (Economic Perspective) From an economic perspective, the markets in which SHPGs can gain economic benefits have been expanding as interest in carbon-neutral power systems has grown. For instance, SHPGs not only serve their primary purpose of providing local generation resources to reduce internal demand, but they also have become eligible for dual settlement in the energy market and for trading emission rights based on the kWh generation, thus increasing their potential for economic gain with considerable life expectancy from 30 to 70 years, whereas the life expectancy with the guaranteed operations efficiency of BESS is generally around 15 years [34].

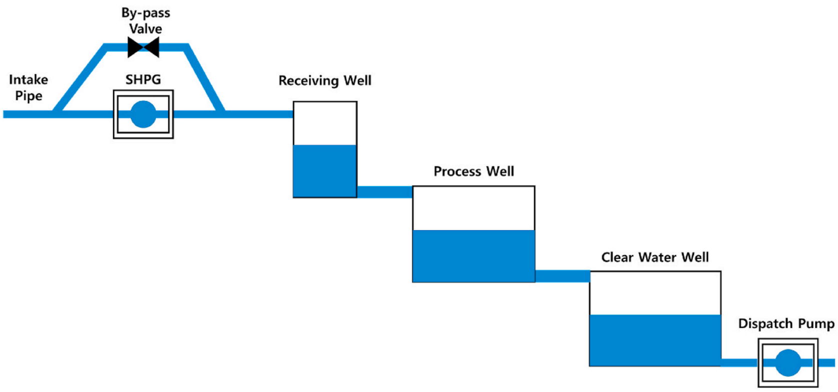


Fig. 1. Operation process of the MWPF

2.2. Benefits of participating in variability mitigation incentive market with SHPGs

Greater penetration of the renewable resources has been causing several reliability issues by the innate variability differing from the forecasted output that cannot be controlled perfectly by the central system operator. Thus, numerous nations have launched the new market opportunity for the market participants with the renewable resources to control their own variability in decentralized manner as mitigations measures normally referred to one of the market-based measures.

Table 1 represents the settlement rules introduced as the market-based measures for the variability control of the renewable resources. kWh^{RT}, kWh^{DA}, and RE^{Cap} represent the energy generated in RT and DA phases by the renewable resources and capacity of the renewable resources registered as a single portfolio.

Among the nations listed in the table, it is possible to confirm an implication from criteria for the reference bands that the primary purpose of the incentive was to control the variability from the SOs' perspective as the market-based measure. As the market maturity or the management philosophy differs, there are markets imposing penalty only or providing chances for the incentive as well. In the case of GB and the Republic of Korea, both of penalty and incentive are applicable for the market participant. In India and Australia, the market based measures are also utilized by the SO as well as possible mitigation measures. One of the common implication from the SOs' perspective in both nations imposing penalty could be the fact that the renewable resources listed in the table below have been causing the severe operations reliability issues in the past [35–40].

Under these market-based measures, market participants can make efforts to reduce forecast errors and either pursue incentives or avoid penalties by coordinating renewable energy resources with energy storage systems. Among the energy storage system options, many studies have chosen BESS as the primary option for coordination strategies. Wei. et al. [41] proposed the optimal bid strategies for the wind power generators in coordination with BESS based on the reinforced learning applied for the wind power forecasts. Choi et al. [42] also proposed the bid strategy for the PVs in coordination with BESS to maximize the revenue from the forecast incentive. However, as BESS does not produce energy by itself, predicting its state of charge and its ability to participate in mitigation is difficult, which can be a disadvantage for continuous use. Moreover, it is highly likely for the market participants with BESS to be exposed to issues related to the operations reliability such as fire incidents and greater cost of operation and maintenance [43]. As aforementioned in Section 2.1, SHPGs can be considered to be the carbon neutral generation resources with relatively stable output characteristics as the mitigation resources without apprehension on fire incidents, but with much longer life span than the life span of BESS [44]. Thus, SHPGs can be considered to be candidate resources with such versatility in utilization as mitigation resources for the renewable generators with high degree of the variability.

2.3. Utilization of SHPGs as variability mitigation resources

Past studies on the operation methods of SHPGs has focused on the characteristics of their installation sites and maximizing profit. Gono. et al. [45] suggested the use of SHPGs controlled by bypass pipes in water purification plants, while Gómez-Llanos. et al. [46] also proposed the design and use of SHPGs in such plants. Yoshioka. et al. [47], Almeida et al. [48], and Liu et al. [49] offered operational approaches for SHPGs installed at dams and reservoirs, aiming to maximize profit by considering energy prices with hourly granularity and operation costs. Similarly, Punys. et al. [50], Beltran. et al. [51], and Bousquet. et al. [52] advocated for active utilization of SHPGs in water treatment plants, with revenue streams limited by energy trades and kWh generation, as well as operational expenses. However, due to insufficient altitude differences for SHPG installation in process wells at water treatment plants, Beltran. et al. [51] recommended diversifying revenue streams to improve economic feasibility. Despite these suggestions, none of the studies addressed the use of SHPGs to mitigate variability from renewable resources in the power system. For such reasons, utilization of the SHPGs as the mitigation resources were considered and suggested through this paper.

The method of utilizing SHPGs as variability mitigation resources that we suggest in this paper can be observed in Fig. 2 below. As illustrated in the figure, the market participant considered in the simulation was postulated to possess the representative types of the renewable sources such as PV and WPG as the resources in independent operations and PV + BESS and WPG + BESS as the resources in coordination. The algorithm can be classified into two phases that are the phases in DA and ID. In the algorithm for DA bid, based on availability of the resources, parameters in the market environment and participation eligibility by the market regulation, the resources aggregated are classified whether they are capable of providing the responses in the market. Once the participations schedule

Table 1
Variability tolerance and technical criteria in the nations with the forecast incentives or regulations.

Nation	Resource	Incentive	Penalty	Forecast Error	Reference Band	Reference
GB	WPG	O (Accuracy Dependent)	O (Financial)	$\frac{\lvert kWh^{RT} - kWh^{DA}\rvert}{RE^{Cap}}$	Seasonally Speciifed by the SO	[35,36] [37,38]
India	PV & WPG	X	O (Financial)	$\frac{\lvert kWh^{RT} - kWh^{DA}\rvert}{RE^{Cap}}$	15% (Differs by the States)	
AU	RE ≥ 30 MW	X	O (Non-financial)	Mean Absolute Error	Specified by the TSO	
ROK	RE ≥ 20 MW	O (Accuracy Dependent)	O (Non-financial)	$\frac{\lvert kWh^{RT} - kWh^{DA}\rvert}{RE^{Cap}}$	Specified by the SO	

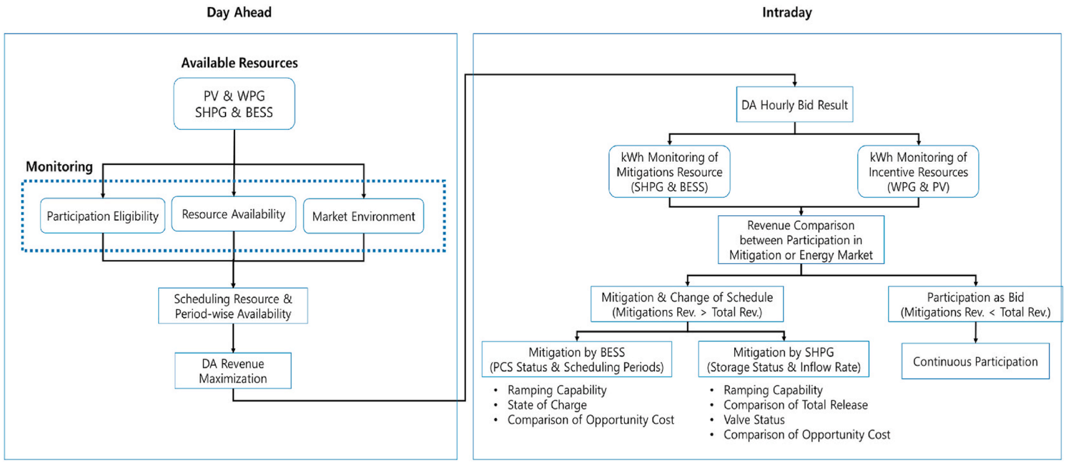


Fig. 2. Operations Flow of Scheduling algorithm Proposed.

in revenue maximizing manner is determined, the coordination in the intraday phase is in effect based on the hourly bid result. In the intraday coordination, the hourly scheduling decisions are determined by comparing the hourly potential revenue to be generated at each call. The mitigations resources are coordinated to adjust their kWh output when the potential revenue from participations in the mitigation is greater than sum of the revenue and losses in the period as planned in the DA bid. As illustrated in the figure, as long as the potential revenue from the mitigation is less than the potential revenue from the DA bid in the period, the resources are coordinated not to change their outputs.

The control variables in the mitigation resources vary depending on the type of resource. In the case of SHPGs as mitigation resources, the control variables include the valve status as a binary variable, the storage status of the MWPF installed at the site, the inflow rate of the SHPGs, and the ramping capability within the output range. In the case of BESSs as mitigation resources, the state of charge (SoC) and the ramping capability within the power conversion system (PCS) limit are the control variables. The opportunity cost considered in scheduling each mitigation resource is the same as the potential revenue that would occur in the designated periods in the absence of schedule adjustments.

The proposed scheduling algorithm can generate profits through the variability incentive market, as discussed in Subsection 2.2. Further, it can also derive profits from kWh generation through the utilization of the resource portfolio, profits from renewable energy certificates (RECs) sales, and profits through carbon emissions trading. Table 2 represents price signals that the scheduling algorithm may consider when it is adopted in the Republic of Korea, one of the countries that operates the variability incentive market as noted in Table 1 and, as will be discussed later, was used as the simulation environment for the algorithm in this paper.

The scheduling algorithm considers basically two different price signals: the Korean allowance unit (KAU21), which is the name of

Table 2
Environment of the market settlement for the renewable resources in the Republic of Korea.

Resource	PV & SHPG & WPG (Independent)	PV + BESS in the Main Land (Coordinated)	WPG + BESS in the Main Land (Coordinated)		WPG + BESS in the Island (Coordinated)	
Periods for REC Multipliers	00:00–24:00	00:00–09:00/ 16:00–24:00	Spring&Winter	09–12	Spring&Winter	05-10/ 18-23
			Summer	13–17	Summer	13-15/ 19-21
			Fall	18–21	Fall	05-10/ 18-23
kWh Generation Measurement Criteria for REC Calculation	kWh Generation at Installation Site	kWh Discharged by BESS Coordinated during Periods for Multipliers				
Mulitplier for REC	Differ by Installations Sites (Between 0.7 and 2)	5		5		5
REC Settlement	REC with Multiplier for kWh Generation Exported					
SMP Settlement	Proportional to kWh Generation Metered at point of common coupling of the Resources & SMP for 24 Hours in a Day					
KAU21 Settlement	Proportional to kWh Generation Exported from the Renewable Resources & Price of KAU21 in a Day					

GHG emissions rights in the Republic of Korea, and the system marginal price (SMP) plus REC. Currently, renewable resources are eligible for dual settlement in trades of GHG emission rights settled by KAU21 while maximizing revenue from the primary energy market. As can be seen from Table 2, the scheduling periods eligible for opportunities to maximize the revenue differ from each other whether those are installed in the mainland or in the island as well as the type of renewable resources. The periods eligible for the REC settlement with the multipliers differ seasonally and locally by the resource types due to the different characteristics of the peak load differing regionally. In the case of the renewable resources in independent operations, the multipliers vary upon the installation sites. The kWh energy eligible for the SMP settlement is the kWh energy metered at the point of common coupling and the kWh energy eligible for the REC settlement differs by whether its energy discharged by the BESS or exported to the external grid by the renewable resources coordinated with the BESS. In the case of the settlement by KAU21, it is proportional to the energy exported to the external grid and dependent upon the intraday price determined in the auction.

3. Optimal bid and coordination strategy of the market participant with SHPGs

The concept of scheduling algorithm suggested in Section 2 is mathematically formulated in detail in this chapter. As explained through Fig. 2, the scheduling algorithm is divided into the DA phase and ID phase. Section 3.1 focuses on the DA phase, while Section 3.2 covers the ID phase, determining the participation schedule in the mitigation incentive market by considering the availability of SHPGs.

3.1. Strategy for optimal day ahead bid

The revenue stream from the portfolio of the owner of the renewable resources, mentioned in Subsection 2.3, can be modelled using Eq. (1). M^{REC}, M^{GHG}, M^{W} and, $C^{O\&M}$ represent the revenue streams from participation in the electricity market, GHG emission trade rights, scheduled sales of the water resources, and the gross loss from operations and maintenance cost.

$$maximise\ M^{REC} + M^{GHG} + M^{W} - C^{O\&M} \tag{1}$$

The revenue stream from the participation in the REC market denoted to be M^{REC} consists of the sub-streams from the resources in coordination for eligibility of the settlement with the multipliers represented by M^{Co}, and the resources in independent operations denoted by M^{Ind} as follows:

$$M^{REC} = M^{Co} + M^{Ind} \tag{2}$$

M^{Co} in Eq. (2) can be modelled as Eq. (3) below. $R_{c,h}$, REC_c and REC_c^w represent the revenue stream from participation in the REC market settled by the SMP and kWh energy eligible for settlement with and without the resource-specific multiplier W_c. X_c, and RCB_c represent prices eligible for the settlement by REC, and the reliability incentives introduced to lower the operating points of the generation resources coordinated with the BESS which is proportional to 5% of the kWh energy discharged from the BESS since 2021 by the energy regulator in the Republic of Korea.

$$M^{Co} = \sum_{h\in H}\sum_{c\in C} R_{c,h} + REC_c^w W_c X_c + REC_c X_c + RCB_c \tag{3}$$

Eq. (4) below represents a sub-stream from the reliability incentive introduced that is proportional to 5% of the kWh energy discharged from the BESS. γ represents the coefficient that is 0.05. The revenue settled by the SMP and kWh energy eligible for the REC settlement with and without resource-specific multipliers can be modelled using Eqs. (5) and (6), where $P_{c,h}^{cc}$ represents the kWh energy exported to the power system and $P_{c,h}^{R}$, $P_{c,h}^{R2B}$, and $P_{c,h}^{B2G}$ represent the output forecasted of the renewable resources coordinated with the BESS, charged and discharged by the BESS coordinated with the renewable energy, respectively. The set HX represents the scheduling window ineligible for REC settlement with the resource-specific multiplier.

$$RCB_c = \gamma \bullet \sum_{h\in H}\sum_{c\in C}\left(P_{c,h}^{B2G}\right) \bullet smp_h + \gamma \bullet \sum_{h\in H}\sum_{c\in C}\left(P_{c,h}^{B2G}\right) \bullet W_c X_c \tag{4}$$

$$R_{c,h} = P_{c,h}^{cc} \bullet smp_h, P_{c,h}^{cc} = P_{c,h}^{R} + P_{c,h}^{B2G} - P_{c,h}^{R2B} \tag{5}$$

$$REC_c = \sum_{h\in H}\sum_{c\in C}\left(P_{c,h}^{R} - P_{c,h}^{R2B}\right), REC_c^w = \sum_{h\notin HX}\sum_{c\in C}\left(P_{c,h}^{B2G} - P_{c,h}^{R2B}\right) \tag{6}$$

M^{Ind} in Eq. (2) can be modelled using Eq. (7). $R_{x,h}$, REC_x^w, and X_x represent the revenue stream from participation in the electricity market settled by the SMP, kWh energy eligible for settlement with the resource-specific multiplier W_x, and prices eligible for settlement by the REC, respectively.

$$M^{Ind} = \sum_{x\in X}\sum_{h\in H} R_{x,h} + \left(REC_x^w\right) W_x X_x \tag{7}$$

The revenue stream from the renewable resources in independent operations can be modelled using Eqs. (8) and (9), respectively.

$P^{R}_{x,h}$ and $P^{cc}_{x,h}$ represent the kWh energy generated by the renewable resources and exported to the power system.

$$R_{x,h} = P^{cc}_{x,h} \bullet smp_h \tag{8}$$

$$REC^{w}_{x} = \sum_{h \in H} \sum_{x \in X} \left(P^{cc}_{x,h} \right) \tag{9}$$

The kWh generation metered at the point-of-common-coupling (PCC) of each generation resource and exported to the power system can be modelled using Eq. (10), where $P^{S}_{x,h}$, $P^{W}_{x,h}$, and $P^{L}_{x,h}$ represent the kWh energy exported to the power system by the PV generators and SHPGs at the MWPF and dam, respectively. The total output of the independent generation resources was separately designed for the additional generation resources to be added to the portfolio that might not be the renewable resources in further research. $P^{R}_{x,h}$ represents the output forecasted of the renewable resources in independent operations eligible for incentive from the variability control.

$$P^{cc}_{x,h} = P^{S}_{x,h} + P^{W}_{x,h} + P^{L}_{x,h}, P^{R}_{x,h} = P^{S}_{x,h} \tag{10}$$

The operational constraints of the coordinated BESS can be modelled using Eq. (11) below, where SoC^{max}_{c} and SoC^{min}_{c} represent the maximum and minimum operational limit of the BESS. $SoC_{c,h}$, α, β, and τ represent the hourly status of SoC, the coefficients representing operations efficiencies of charging and discharging of the BESS, and the operations limit specified by the reliability organization in the Republic of Korea. Eq. (12) represents the technical limits of the kWh energy that can be charged and discharged by the BESS simultaneously, where PCS^{max}_{c}, $\delta^{c}_{c,h}$ and $\delta^{d}_{c,h}$ represent the limit and the binary decision variables for charging or discharging, respectively. Eq. (13) represents constraint for the operations decision to whether charge or discharge the BESS.

$$SoC^{min}_{c} \leq SoC_{c,h-1} + \alpha P^{R2B}_{c,h} - \frac{P^{B2G}_{c,h}}{\beta} \leq SoC^{max}_{c} \tau \tag{11}$$

$$0 \leq P^{R2B}_{c,h} \leq PCS^{max}_{c} \delta^{c}_{c,h}, 0 \leq P^{B2G}_{c,h} \leq PCS^{max}_{c} \delta^{d}_{c,h} \tag{12}$$

$$\delta^{c}_{wb,h} + \delta^{d}_{wb,h} \leq 1 \tag{13}$$

The kWh output constraints of the SHPGs at the dam and MWPF can be modelled using Eq. (14), where $P^{L}_{x,h}$, $P^{W}_{x,h}$ and φ represent the kWh output by SHPGs at the dam and MWPF, water density. g and μ_x represent gravity acceleration and compound efficiencies. $Q^{L}_{x,h}$ and $Q^{W}_{x,h}$ represent the flow rate in cm/h at each SHPG.

$$P^{L}_{x,h} = \varphi \bullet H_x \bullet g \bullet Q^{L}_{x,h} \bullet \mu_x, P^{W}_{x,h} = \varphi \bullet H_x \bullet g \bullet Q^{W}_{x,h} \bullet \mu_x \tag{14}$$

The flow rate must be limited by the reliability of the SHPGs, as shown in Eqs. (15) and (16), respectively, where Q^{Lmax}_{x}, Q^{Wmax}_{x}, Q^{Lmin}_{x}, and Q^{Wmin}_{x} represent the minimum and maximum flow limits of the SHPGs at the dam and MWPF, respectively. $\delta^{L}_{x,h}$ and $\delta^{W}_{x,h}$ represent the decision variable for the SHPGs installed at intake sources and the treatment facilities to generate the kWh energy or not in consideration of the water dispatch schedules.

$$Q^{Lmin}_{x} \bullet \delta^{L}_{x} \leq Q^{L}_{x,h} \leq Q^{Lmax}_{x} \bullet \delta^{L}_{x}, Q^{Wmin}_{x} \bullet \delta^{W}_{x} \leq Q^{W}_{x,h} \leq Q^{Wmax}_{x} \bullet \delta^{W}_{x} \tag{15}$$

$$\delta^{L}_{x,h} \leq 1, \delta^{W}_{x,h} \leq 1 \tag{16}$$

The gross amount of the water resources to be utilized in the day is constrained by Eq. (17), where $Q^{B}_{x,h}$, Q^{WTot}_{x}, and Q^{LTot}_{x} represent the flow rate via the bypass pipe and the intraday (ID) demand of the water resources at the subject MWPF, and the release demand intraday at the subject dam, respectively.

$$\sum_{h \in H} \left(Q^{L}_{x,h} \right) = Q^{LTot}_{x}, \sum_{h \in H} \left(Q^{W}_{x,h} + Q^{B}_{x,h} \right) \geq Q^{WTot}_{x} \tag{17}$$

The Operational constraints on the site capacity at the MWPF can be modelled using Eqs.18–20. S^{max}_{x}, S^{min}_{x} and S_x represent the maximum and minimum process capacity, and the hourly capacity status at each facility. $L_{x,h}$, D_x, $Q^{out}_{p,x,h}$, and T represent the average loss, intraday demand on the water resources, water dispatch at each hour, and time delay for the filtration process of the subject site.

$$S_{x,h+T+1} = S_{x,h+T} + Q^{W}_{x,h} + Q^{B}_{x,h} - \sum_{p \epsilon P} \left(Q^{out}_{p,x,h+T} \right) - L_{x,h} \tag{18}$$

$$\sum_{h \epsilon H} \sum_{p \epsilon P} \left(Q^{out}_{p,x,h} \right) \leq D_x \tag{19}$$

$$S^{min}_{x} \leq S_{x,h} \leq S^{max}_{x} \tag{20}$$

The dispatchable water resources in each period were modelled using Eq. (21), where $\Gamma_{p,x}$, $P_{p,x,h}$ and $u^{on}_{p,x,h}$ represent a binary decision variable for pump operations, outflow-to-kWh ratio, and the kWh energy consumed.

$$Q^{out}_{p,x,h} = \Gamma_{p,x} \bullet P_{p,x,h} \bullet u^{on}_{p,x,h} \tag{21}$$

The revenue stream from the trade of GHG emission rights can be designed using Eq. (22), where K_x and π^{curt}_x represent the prices of GHG emission trade rights by KAU21 and the ratio of the GHG curtailed by the clean generation by SHPGs, respectively.

$$M^{GHG} = K_x \bullet \sum_{h\epsilon H}\sum_{x\epsilon X}\left(P^W_{x,h} + P^L_{x,h}\right) \bullet \pi^{curt}_x \tag{22}$$

The revenue stream from sales of the water resources to municipal waterworks can be designed using Eq. (23), where π^W_x and π^{WF}_x represent the sales prices of the water resources after the dispatch and the forward contract, respectively.

$$M^W = \sum_{h\epsilon H}\sum_{x\epsilon X}\sum_{p\epsilon P}\left(Q^{out}_{p,x,h}\right) \bullet \pi^W_x + Q^{WTot}_x \bullet \pi^{WF}_x \tag{23}$$

The cost elements in the model in the present model can be summarized as Eq. (24), where C^{Con} and C^W represent the operational cost of the BESS and the electricity retail cost by dispatch pumps, respectively. The O & M cost of the SHPGs at the dam was not considered because the cost incurred after the operations was negligible.

$$C^{O\&M} = C^{Con} + C^W \tag{24}$$

The components of O & M cost of the BESS can be modelled using Eq. (25), where C^{op}_c and C^w represent the kWh energy cost of the subject dispatch pumps at each site and the variable O & M cost of the BESS in coordination and independent operation, respectively. $\pi^U_{x,h}$ represents the hourly retail electricity price applicable for the industrial end-users after their actual kWh energy consumed, whereas π^F_x represents the forward price applicable for the kW capacity in the two-part tariff system. E^F_x represents the kW capacity at each subject MWPF based on the kW capacities of the dispatch pumps.

$$C^{Con} = C^{op}_c \sum_{h\epsilon H}\sum_{c\epsilon C}\left(P^{R2B}_{c,h} + P^{B2G}_{c,h}\right), C^W = \sum_{h\epsilon H}\sum_{x\epsilon X}\sum_{p\epsilon P}\left(P_{p,x,h}\right) \bullet \pi^U_{x,h} + \sum_{x\epsilon X} E^F_x \bullet \pi^F_x \tag{25}$$

The DA bid schedule can be modelled using Eq. (26), where MR^{DA}_h and AR^{DA}_h represent the portfolio-wise bid after the DA schedule with the kWh generation from the major generation resources eligible for the forecast incentive in the RT coordination and the kWh generation from the mitigation resources ineligible for the forecast incentive with hourly granularity, respectively.

$$MR^{DA}_h = \sum_{c\epsilon C}\left(P^{cc}_{c,h}\right) + \sum_{x\epsilon X}\left(P^R_{x,h}\right), AR^{DA}_h = \sum_{x\epsilon X}\left(P^L_{x,h} + P^W_{x,h}\right) \tag{26}$$

3.2. Optimal method of the intraday coordination

The major purpose of the coordination in the second stage is to maximize the profits from the revenue streams generated via the participation in the forecasting incentive market and the actual energy traded in the REC market. Elements in the revenue stream in the second stage are virtually the same as considered in the first stage except for the revenue stream by the participation in the forecast incentive market represented by M^{DER} and the gross loss from operations costs and financial penalty represented by C^{Var} as designed in Equation (27) below.

$$maximise \quad M^{REC} + M^{DER} + M^{GHG} + M^W - C^{Var} \tag{27}$$

Considering the current market rules for the forecast incentive, the revenue stream can be modelled using Eq. (28), where $IPFP^{\sigma}_h$ and FP^{σ} represent the eligibility indicators for incentive settlement. $IPFP^{\sigma}_h$ represents the decision variable with hourly granularity that the resources are eligible for the incentive. FP^{σ} represents price of the incentive determined after magnitudes of the error occurred with hourly granularity. Because mitigation resources are not eligible for the forecast incentive, the kWh generation by the mitigation resources was excluded from the bid eligible for the forecast incentive.

$$M^{DER} = \sum_{h\epsilon H}\left[\left(IPFP^{\sigma}_h \times FP^{\sigma}\right) \times \left(MR^{DA}_h\right)\right] \tag{28}$$

Eq. (29) represents the settlement criteria in the forecast incentive market. CF^{RT}_h and FE_h represent the capacity factor of the major generation resources eligible for the forecast incentive and the gross forecast error relative to the total capacity of the portfolio. The capacity factor thereof is represented to avoid the circumstance that the MPs become eligible for the incentive as long as the forecasted error is null without any contribution. Because the constraints comparing the variables each other are in non-linear formulation, the non-linear constraints in the present formulation are linearized to be computable in mixed integer linear programming.

$$IPFP_h = \begin{cases} 1 & CF^{RT}_h \geq 10\%, |FE_h| \leq 8\% \\ 0 & o/w \end{cases} \tag{29}$$

The settlement process in the forecast incentive market can be modelled using Eq. (30). As represented below, the resources eligible for the incentive are settled for 3 or 4 KRW/kWh for the kWh generation bid in DA market as long as the forecast error is below 8%.

$$FP^{\sigma} = \begin{cases} 3 & IPFP_h = 1, 6\% < |FE_h| \leq 8\% \\ 4 & IPFP_h = 1, 0\% \leq |FE_h| \leq 6\% \\ 0 & o/w \end{cases} \quad (30)$$

The definition of the forecast error can be modelled using Eq. (31), which is the difference between the portfolio-wise DA bid schedule and the actual kWh contribution toward the power system denoted by PCC_h^{RT} in Eq. (32) relative to Cap_r^{DER}, the total capacity of the primary generation resources eligible for the forecast incentive.

$$FE_h = \frac{(MR_h^{DA} + AR_h^{DA}) - PCC_h^{RT}}{Cap_r^{DER}} \times 100\% \quad (31)$$

$$PCC_h^{RT} = \sum_{c\epsilon C} \left(P_{c,h}^{cc}\right) + \sum_{x\epsilon X} \left(P_{x,h}^{cc}\right) \quad (32)$$

However, for flexible operations requiring violations of the dispatch schedules predetermined under certain circumstances, penalty constraints are introduced as Eq. (33), where ξ_x^L, ξ_x^W, and ξ_c^B represent the hourly penalty by the SHPGs at the dam, MWPF, and the BESS with the renewables.

$$C^{Var} = \xi_x^L + \xi_x^W + \xi_c^B + C^{O\&M} \quad (33)$$

Eq. (34) represents the penalty constraints on SHPGs at the MWPF and the dam by the deviation from the schedule predetermined by the DA schedule, where the set HCW and HCL represent the hours determined by the DA schedule for the water dispatch and the release unplanned in cubic meters per hour, respectively. The coefficients denoted by ϕ_x^W and ϕ_x^L represent coefficients of opportunity cost designed in consideration of possible operations at each granularity to avoid such operations.

$$\xi_x^w = \sum_{h\in HCW} \sum_{x\in X} \sum_{p\in P} Q_{p,x,h}^{out} \bullet \phi_x^w, \xi_x^L = \sum_{h\in HCL} \sum_{x\in X} Q_{x,h}^L \bullet \phi_x^L \quad (34)$$

Eq. (35) represents penal constraints on the BESS by violations of the DA schedule at their discretion, regardless of the scheduling periods eligible for the settlement with the multipliers with its own risk by coefficient of the opportunity cost denoted by ϕ_c^B. ϕ_c^B is the difference between the average SMP during periods for the multiplier settlement and the expected settlement prices for kWh energy discharged. The sets *HX* and *HO* represent the scheduling periods ineligible and eligible for the REC settlement with resource-specific multipliers, respectively.

Table 3
Specification of the Resources used in the Simulation.

Type	Element					
Renewables with BESS	PCS Capacity of BESS (PCS_c^{max})	Round-trip Efficiency of BESS (α, β)	Max. SoC of BESS (SoC_c^{max})	Min. SoC of BESS (SoC_c^{min})	Capacity of BESS	Capacity of PV/WPG
$(PV \& BESS)_{Sejong}$	1,000 kW	95%	3,600 kWh	200 kWh	4,000 kWh	1,625 kW
$(WPG \& BESS)_{Hwasoonon}$	1,250 kW	95%	3,200 kWh	800 kWh	4,000 kWh	16,000 kW
$(WPG \& BESS)_{Jeju}$	2,000 kW	95%	3,200 kWh	800 kWh	4,000 kWh	8,000 kW
SHPGs	Net Head (m)(H_x)	Range of Flow Rate (m^3/s)($Q_{x,h}$)	Compound Efficiency (%)(μ_x)	Nominal Max. Output (kW)($P_{x,h}$)	Site Constraint (Type)	Turbine (Type)
$SHPG_{Daecheong,1}$	4.39	10.92	0.846	400	Control Reservoir	Tubular
$SHPG_{Daecheong,2}$	4.39	10.92	0.846	400	Control Reservoir	Tubular
$SHPG_{Yongdam,1}$	46	$Q < 6.16$	0.824	2,300	DAM	Francis
$SHPG_{Yongdam,2}$	46	$Q < 6.70$	0.815	2,130	DAM	Francis
$SHPG_{Seongnam}$	18	$1.0 < Q < 2.6$	0.838	340	MWPF	Francis
$SHPG_{Buan}$	19.6	$0.3 < Q < 1.09$	0.915	193	MWPF	Tubular
Load Resources	Dispatch Pumps ($kW/\#$) ($P_{p,x,h}$)	Water Demand (m^3) (D_x)	Dispatch Capability (m^3/hr) ($P_{p,x,h}$)	Storage (m^3/d) (S_x^{max})	Ave. Intraday Utilization Factor (%)	
$S_{SeongNam}$	5,900/8	522,925	24,794	425,000	66.5	
S_{Buan}	1,566/6	58,252	5,832	87,000	67	

$$\xi_c^B = \sum_{h \in HX} \sum_{c \in C} P_{c,h}^{B2G} \bullet \phi_c^B, \phi_c^B = \left(W_c^R X_c^R + \sum_{h \in HO} \frac{smp_h}{h} \right) - smp_h \tag{35}$$

4. Simulation Setup

The scheduling algorithm introduced in Section 3 is simulated from the perspective of the water resources corporation in the Republic of Korea. The water resources corporation possesses renewable resources in independent operations and coordination, and the actual specifications of those resources were listed in Subsection 4.1. Other information used in the simulation is specified in Subsection 4.2. The simulation was carried out by GAMS [53] and an AI-package embedded in MATLAB [54].

4.1. Specifications of the resources in the portfolio

The resource portfolio of the water resources corporation used in the simulation is composed of three types of renewable energy sources. Firstly, there are renewable sources that operate with BESS. These renewable sources may utilize BESS to obtain forecast incentives in the intraday market based on the bid in the day-ahead market, but the utilization of BESS may vary depending on the hourly status of SoC. $(PV \& BESS)_{Sejong}$, $(WPG \& BESS)_{Hwasoonon}$ and $(WPG \& BESS)_{Jeju}$ in Table 3 are the renewable sources with BESS listed in the portfolio of the water resources corporation. Secondly, there are SHPGs installed in MWPFs and dams. These SHPGs are used to mitigate the variability of the renewable resource portfolio, to pursue profits through participation in the electricity market. SHPGs installed in MWPFs are also used to reduce the net energy bill at each MWPF. $SHPG_{Seongnam}$ and $SHPG_{Buan}$ in Table 3 are SHPGs installed in MWPF Seongnam and MWPF Buan. $SHPG_{Daecheong,1}$, $SHPG_{Daecheong,2}$, $SHPG_{Yongdam,1}$ and $SHPG_{Yongdam,2}$ are SHPGs installed in Daecheong dam and Yongdam dam. $S_{SeongNam}$ and S_{Buan} are the internal load of each MWPF. Lastly, there are renewable sources that operate independently without the installation of BESS. The independently operated renewable sources owned by the water resources corporation assumed in the simulation are PVs, which are reflected by summing up to a total of 21,015 kW.

In order to consider diverse technical characteristics of resources in the portfolio, the resources requiring different scheduling periods and constraints were introduced in the simulation. At the initial scheduling periods, the initial SoC of the BESS and the initial values of the wells at each MWPF were set to be the minimum SoC specified and the values considered average utilization factor. In MWPF at Seongnam, there are 6 primary pumps and 2 ancillary pumps to control the water dispatch. In MWPF at Buan, there are 4 primary pumps and 2 ancillary pumps to control the water dispatch. The maximum dispatch capability was postulated to be the same as the total dispatch capability by the pumps available. The nominal net head for each pump in MWPF at Seongnam was set at 66 m and the nominal net head for each pump in MWPF at Buan was set at 50 m for the primary and 64 m for the ancillary pumps.

4.2. Market parameters in the simulation

According to classifications in the two-part tariff system in the Republic of Korea, MWPFs are currently classified to be the facility obligated to contract the forward capacity with 24 h of electricity consumption postulated. Cost of the forward contract for MWPF at Seongnam and Buan were calculated to be KRW 31,059,000 and KRW 7,629,552 in consideration of the total capacity of the primary dispatch pumps in each facility and price of the forward contract for 7,308 KRW/kW. Intraday electricity consumption planned in Seongnam and Buan was planned to be 102,000 kWh and 25,056 kWh.

The financial parameters for the revenue from participation in trades of the GHG emissions rights that are prices of KAU21 in KRW/kgCo2eq and conversion factor of GHG in kgCo2eq/kWh were considered in the simulation to be 20 KRW/kgCo2eq and 0.466 kgCo2eq/kWh reflecting the electricity sector in Korea. The price and multiplier of REC in the present date that were 36.016 KRW/kWh, the multiplier of 5 for the renewable resources in coordination and 1 for the resources in independent operations were considered in the simulation. Similar to the two-part tariff system for the electricity, the water tariff system in Korea is also in two-part tariff system. The forward contract price in KRW/m3 and the water resources dispatched in KRW/m3 was considered to be 302.8 KRW/m3 and 130 KRW/m3.

Electricity prices in the simulation consist of the SMP in the wholesale market and the retail prices provided by KPX (Korea Power Exchange) [55]. In consideration of the locational constraints, the SMPs in the mainland and the island of Jeju differ from each other. The SMP in the mainland on March 30, 2021 for the scheduling periods from 0000 h to 2400 h are 83.05, 82.06, 82.12, 82.18, 82.18, 85.15, 85.15, 85.65, 86.51, 85.62, 86.18, 86.09, 79.91, 82.58, 83.41, 83.65, 86.09, 86.09, 87.28, 87.37, 87.66, 87.76, 84.26, and 84.27 in KRW/kWh. The average and the standard deviation of the SMP in the mainland are 84.68 KRW/kWh and 2.14 KRW/kWh, respectively. The SMP in the same scheduling periods on the island of Jeju are 114.09, 140.16, 136.43, 87.84, 136.9, 88.8, 161.35, 88.8, 153.82, 87.74, 86.18, 86.09, 79.91, 82.58, 83.41, 88.32, 89.12, 89.12, 89.61, 127.33, 144.55, 144.55, and 144.55 in KRW/kWh. The average and the standard deviation of the SMP in island Jeju are 84.68 KRW/kWh and 2.14 KRW/kWh, respectively. The retail electricity prices in KRW/kWh are 56.2, 56.2, 56.2, 56.2, 56.2, 56.2, 56.2, 56.2, 78.5, 108.8, 108.8, 78.5, 108.8, 108.8, 108.8, 108.8, 78.5, 78.5, 78.5, 78.5, 78.5, 78.5, 56.2, and 56.2, which are the same throughout the entire sites in the simulation. The average and the standard deviation of the retail electricity prices are 76.78 KRW/kWh and 21.28 KRW/kWh, respectively.

The date chosen for the current simulation was strategically determined to be March 29th, 2021, based on two key criteria. Firstly, this date exhibited the smallest disparity between the SMP and the retail price of electricity among all dates considered, which was recorded at 22.29%. There is a potential concern if the price discrepancy becomes excessively large; a scheduling algorithm may prioritize exploiting this price difference to maximize revenue, rather than ensuring optimal scheduling. This situation could potentially complicate the accurate assessment of the algorithm's performance. Secondly, the selected date maintained an average capacity factor of 17.84%, which is above the 10% minimum capacity factor required for major generation resources in the simulated environment—the electricity market in the Republic of Korea. Lastly, the chosen date falls within the dry season in Korea. This condition is crucial in evaluating the scheduling algorithm's ability to maintain dispatch schedule even under challenging conditions presented by MWPFs. These rigorous conditions are vital in assessing the robustness and reliability of the proposed algorithm. We formulated the available kilowatt-hour output of each resource in the portfolio by using a forecasting package based on Long-Short-Term-Memory available in MATLAB, taking into account the seasonality of the most recent three years preceding the candidate date [54].

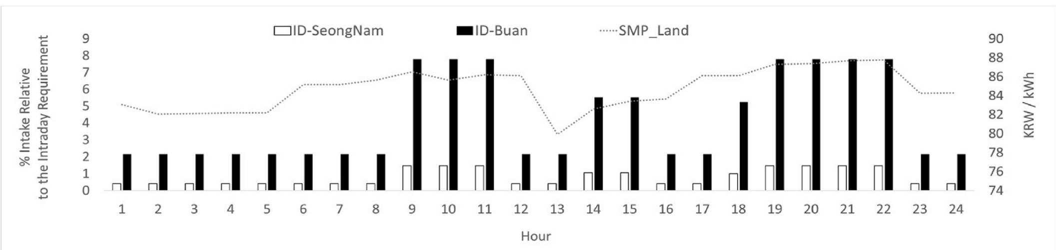
5. Results & discussion

5.1. *Intake and release schedules of SHPGs in MWPFs*

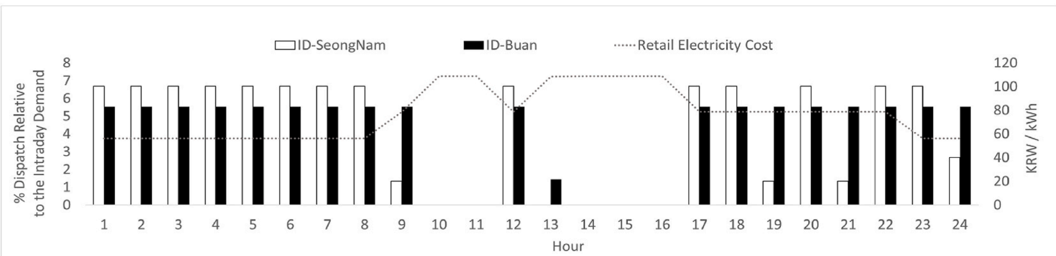
Fig. 3a and b illustrate the intake and release schedule of water resources at MWPF Seongnam and Buan determined by the scheduling algorithm proposed in section 3. During the operation process of MWPF, it is essential to avoid excessive pressure on the intake pipes for system reliability. Furthermore, there is a capacity limit to wells in MWPF, and as mentioned in Section 3, time delays during the water purification process should also be considered. Therefore, it is important for MWPF to disperse the intake amount throughout the scheduling periods. The intake schedule in Fig. 3a demonstrates that the scheduling algorithm ensures the water intake is distributed well across many hours in all MWPFs.

In the case of the intake schedules simulated in Fig. 3a, because the time-variant revenue stream applicable for SHPGs was designed to be the stream from SMP, the intake schedules were determined to be proportional to the changes after SMP with hourly granularity. The intake schedules at MWPFs from the pipes with SHPGs at Seongnam and Buan were simulated to be moderately proportional to patterns of SMP with the correlation of 0.63958 and 0.63962 each [56]. The release schedules at both MWPFs as illustrated in Fig. 3b were also simulated to be related to patterns of the retail electricity prices. Even if without numerical verification with correlation index between the dispatch schedules simulated and patterns of the intraday retail electricity prices, it is illustrated to be obvious that the dispatch schedules were determined in consideration of the price fluctuations in the day by avoiding the dispatch at peak periods.

Those findings above illustrate that the scheduling algorithm contributes to enabling the MWPF to pursue revenue from the SMP by using SHPGs, while simultaneously minimizing electricity usage from dispatch pump operation for cost savings. However, it is important to note that the scheduling algorithm does not always prioritize the pursuit of revenue not from variability mitigation for the MWPF. As can be seen in Fig. 4, the SHPGs show difference in electricity generation in ID schedule from the DA schedule during seven of the twenty-four time windows. In these cases, the SHPGs installed in MWPF target the mitigation of variability from renewable energy sources. Especially, as the SMP prices, noted in Subsection 4.2, are clustered closely around the average of 84.68 KRW/kWh with a small standard deviation of 2.14 KRW/kWh, the SHPGs can be operated even more independently of the highs and lows of the SMP.



(a)



(b)

Fig. 3. (a) Intraday intake schedule at the MWPFs; (b) intraday release schedule at the MWPFs.

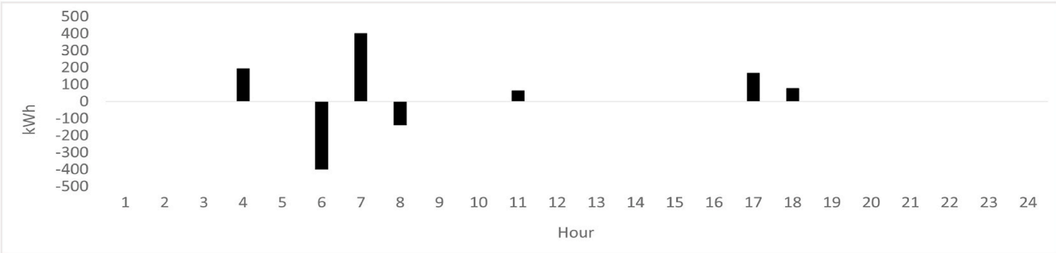


Fig. 4. Portfolio-wise Difference between DA and ID schedules of SHPGs.

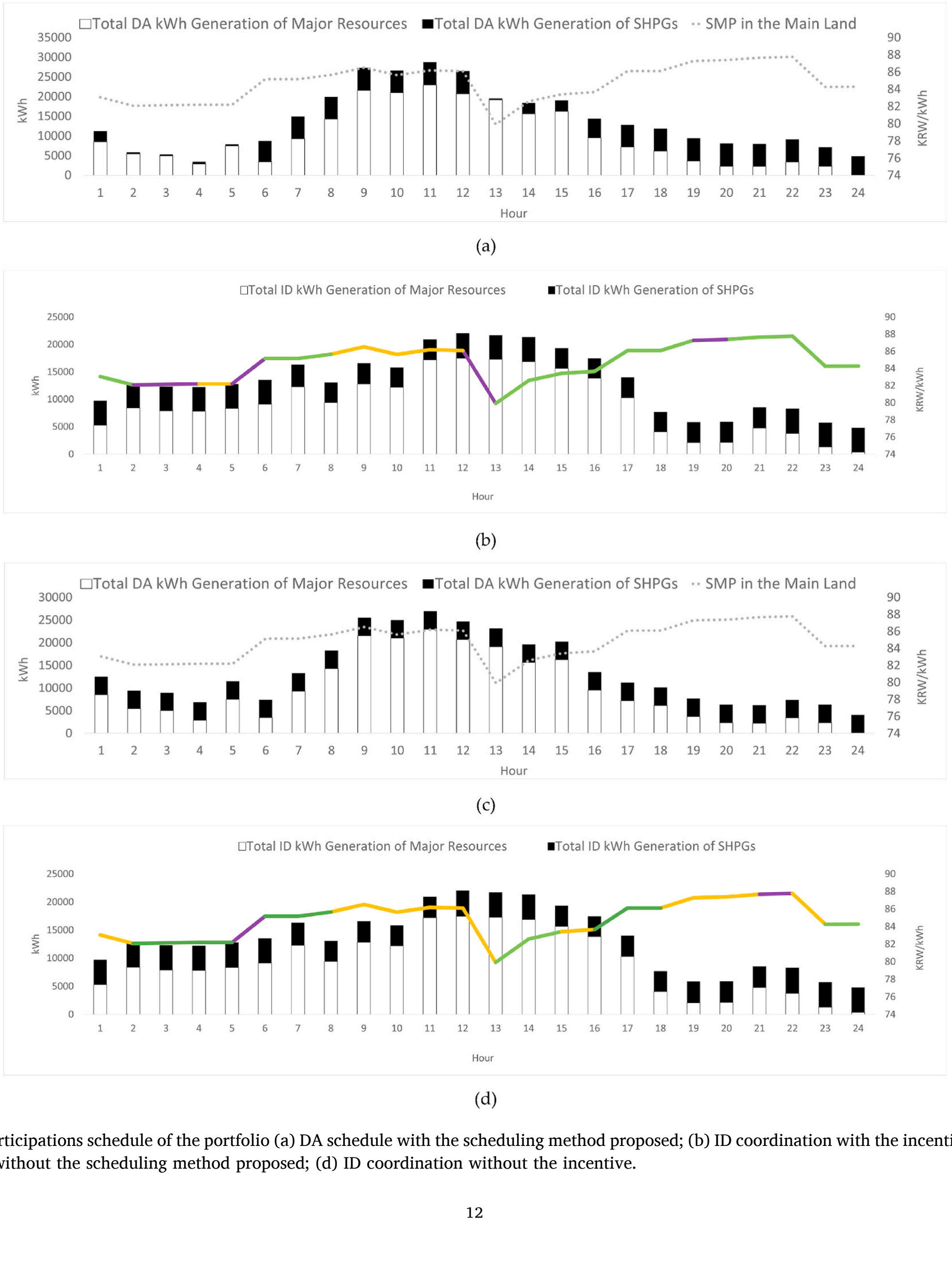


Fig. 5. Participations schedule of the portfolio (a) DA schedule with the scheduling method proposed; (b) ID coordination with the incentive; (c) DA schedule without the scheduling method proposed; (d) ID coordination without the incentive.

5.2. Effect of the scheduling algorithm in mitigating variability

Fig. 5a and b depict the portfolio-wise participation schedule simulated using the proposed scheduling algorithm for DA bid and ID coordination, considering forecast incentives. In contrast, Fig. 5c and d presents the participation schedule based on current practices, where SHPGs' bid schedules are not optimized for DA bid, and ID participation does not consider forecast incentives. In Fig. 5b and d, lines in green, yellow, and purple indicate ranges of the final forecast error that could not be fully mitigated. The forecast error in green corresponds to an error equal to or less than 6%. The error in purple pertains to an error between 6% and 8%, and yellow signifies errors over 8%.

With the coordination method proposed for the DA and ID schedules illustrated in Fig. 5a and b, numbers of sections with the forecast error less or equal to 6%, between 6% and 8%, and over 8% were 14, 5 and 5 periods. Without the coordination method proposed for the DA and ID schedules illustrated in Fig. 5c and d, numbers of sections with the forecast error less or equal to 6%, between 6% and 8%, and over 8% were 10, 2 and 12 periods. This implies that when the scheduling method is not applied, the magnitude of forecast error for each time window could potentially increase.

Further, despite the almost equal opportunities for making revenue through variability mitigation in both cases, there is a difference in the actual average forecast error between the scenarios depicted in Fig. 5a and b and those in Fig. 5c and d. The average forecast error for the simulations in Fig. 5c and d, which are based on current practices, is 4.3%. In contrast, the average forecast error in the scenario depicted in Fig. 5a and b, with the DA bid and ID coordination using the scheduling algorithm is reduced to 1.5%. Therefore, the scheduling algorithm can be seen as helpful in mitigating the variability of renewable energy sources within the portfolio. One notable point is that the forecast error when only optimizing the DA bid based on the scheduling algorithm, without implementing the ID coordination, is 4.5%. This is an increase compared to not applying the scheduling algorithm to both the DA bid and ID coordination. In other words, the scheduling algorithm proposed in this paper can maximize its effectiveness when utilized for both DA bid optimization and ID coordination.

As evident from Fig. 5a and b, there were still windows with a forecast error greater than 8% even after using the scheduling algorithm, and as a result, the participant could not receive the forecast incentive. One plausible reason for this could be in the simulation environment. The scheduling algorithm allows the participant to choose the direction that maximizes revenue by comparing the potential revenue from the forecast incentive with other price signals present in the simulation environment—SMP, REC, and KAU. In the ID coordination carried out by the proposed scheduling algorithm, the windows where participation in mitigation was prioritized included the hours at 0100, 0800, 0900, 1000, 1900, 2000, and 2400. The windows where revenue maximization from the stream by SMP, REC, and KAU was prioritized were hours at 0600, 0700, 1100, 1200, 1400, 1500, 1600, and 1700. The windows where the participant was eligible for the revenue stream from both SMP, REC, and KAU and the forecast incentive were hours at 1800, 2100, 2200, and 2300.

5.3. Contribution of SHPGs in mitigating variability and revenue composition

As discussed so far in Subsection 5.2, the scheduling algorithm can be regarded as effective in mitigating variability under the market-based measures discussed in Subsection 2.2. However, in the simulation resource portfolio, not only SHPGs but also BESSs can participate in mitigating variability and receive forecast incentives. Therefore, using the correlation coefficient, the contribution of SHPGs in mitigating variability through the scheduling algorithm is examined below.

Fig. 6 illustrates the participation schedules of the SHPGs in the current simulation and the forecast error. The negative forecast error depicted in the figure represents the forecast error caused by the kWh energy under-forecasted in the ID coordination. As noticeable in Fig. 6, within the range of kWh energy they can offer, SHPGs in the current simulation tended to provide kWh energy corresponding to hourly patterns of the forecast error. The correlation between the output from the SHPGs and the forecast error was calculated to be 0.69 and can be considered meaningful [56].

Fig. 7 illustrates the participation schedules of the BESSs in the current simulation. In the figure, the superscript B2G (Battery-to-Grid) added in the notation of each BESS indicates that the BESS is discharging and the superscript R2B(Regulation-to-Battery) indicates that the BESS is charging. Unlike SHPGs, BESSs can respond to situations where the ID generation from renewable energy

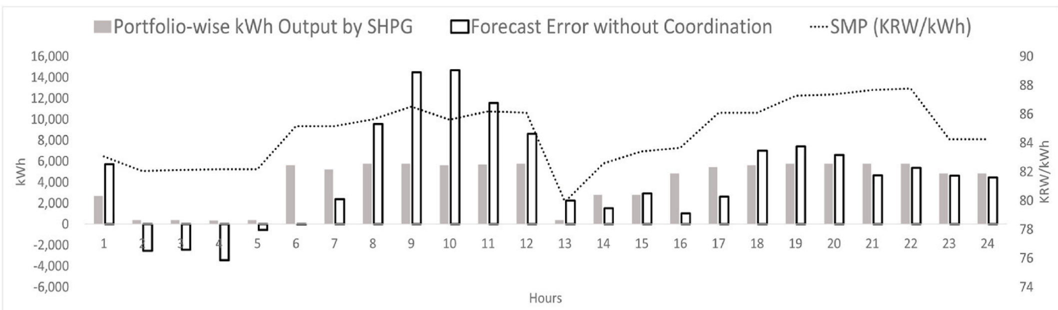


Fig. 6. Portfolio-wise participation schedules of the SHPGs in the ID coordination and Forecast Error.

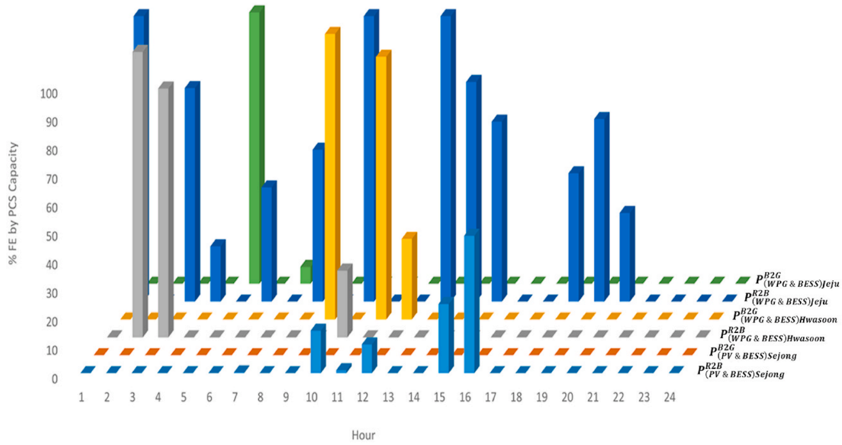


Fig. 7. Differences in operations of the BESS scheduled in the DA and ID coordination.

sources is lower than the DA bid, i.e., over-forecasted, by discharging energy, as well as situations where the ID generation from renewable energy sources is higher than the DA bid, i.e., under-forecasted, by charging. The correlation between the electricity discharged from BESSs and the over-forecast error for each time window is 0.17, while the correlation between the electricity charged into BESSs and the under-forecast error for each time window is 0.01. Both cases fall significantly short of the correlation coefficient of 0.69 for SHPG output and cannot be considered to have a meaningful correlation. Therefore, among the two mitigation resources in the simulation, BESSs and SHPGs, SHPGs can be considered as serving their purposes.

Despite the total capacity of the PCS installed at the BESS being nearly 8.95% of the total capacity of the portfolio, the BESSs were simulated not to deliver a meaningful effectivity in the coordination for the mitigation of variability from renewable resources. As can be seen in Table 2, the BESSs receive a relatively high REC multiplier, suggesting that BESSs prioritize revenue from SMP and REC over variability mitigation and earning forecast incentive. The fact that there is an increase in the forecast error from 1.5% to 16%, when SHPGs are removed in the simulation environment, supports this observation.

5.4. Revenue composition and changes in GHG emissions upon application of scheduling algorithm

Table 4 below illustrates the revenue expectation and the revenue generated by the DA bid and ID coordination under the scheduling algorithm. Revenues in the DA bid and ID coordination were calculated to be $33,845.3 and $34,463.7, with a 1.83% difference. The greatest revenue stream was simulated to be the stream from SMP, REC, KAU21 and the forecast incentive, respectively. The relative smallness of the forecast error incentive in the table can be attributed not only to the low unit price of the incentive in the simulation environment, but also to the fact that while revenues from SMP, REC, and KAU21 can be obtained at all times in addition to the forecast incentive, the incentive can only be obtained in times when its acquisition is possible. The revenue from SMP, REC, and KAU21 was calculated to be $33,846 in the case of the DA bid, but showed a decrease to $33,774 in the ID Coordination. However, the forecast incentive from participating in variability mitigation was simulated to compensate for this decrease. This implies that, the incentive market can be an additional revenue stream for many renewable energy operators who mainly rely on government subsidies, when those operators use the scheduling algorithm in coordinating their resources.

From the cost-effectiveness perspective of the generation resources, the SHPGs were determined to be the most effective in consideration of the total capacity from the SHPGs with 33% of the gross revenue generated by the portfolio, despite the SHPGs were responsible for just 10% of the total capacity of the generation resources aggregated in the portfolio. The least cost-effective generation resources were determined to be the PVs in independent operations that generated only 27.62% of the gross revenue despite their capacities aggregated was responsible for 40% of the total capacity aggregated in the portfolio. The GHG emission curtailed from operations the MWPFs were calculated to be difference between the GHG planned by the kWh consumption postulated in the forward contract and the actual kWh consumption simulated in the ID schedule. The GHG emission postulated by the forward contract at each MWPF Seongnam and Buan was calculated to be 57,834.1 kgCO2eq and 14,206.8 kgCO2eq. The GHG emission was simulated to be curtailed by 38.4% and 24% at MWPF Buan and Seongnam, respectively through the dispatch coordination to avoid inessential pumps operations. This indicates that the new algorithm can contribute in not only mitigating the variability of renewable sources and finding new revenue stream for the renewable energy owners, but also enhancing the eco-friendly aspect of SHPGs.

6. Conclusion

In this paper, we proposed a new scheduling algorithm for the renewable resources portfolio that use SHPGs as a mitigation measure against the variability caused by the inherent characteristics of renewable energy. The scheduling algorithm which is based on optimization method utilizes price signals in the market such as SMP, REC, GHG emissions rights and retail electricity prices, characteristics of renewable sources, and constraints such as water demand or dispatch volume in MWPFs in coordinating the generation of

Table 4
Revenue generated by DA bid and ID coordination.

Revenue Source	DA Bid		ID Coordination	
Total	100%	$33,846	100%	$34,464
SMP	72%	$24,369	71%	$24,469
REC	20%	$6,769	20%	$6,893
KAU21	8%	$2,708	7%	$2,412
Forecast Error Incentive	–	–	2%	$689

renewables in the portfolio. Due to the non-linear nature of those factors considered, we used mixed integer linear programming in formulating algorithm. The algorithm can be modified and utilized in countries where market-based measures such as incentive or penalty policy in mitigating variability of renewable sources are used. After the investigation of benefits of utilizing SHPGs and countries where market-based measures are used, we select the republic of Korea as a base environment in formulating the algorithm in detail and simulating results.

From the simulation results, it was observed that the proposed scheduling algorithm effectively utilized SHPGs as generation resources for mitigating variability, without interfering with the water intake and dispatch schedules of the MWPFs. The algorithm coordinated the intake and dispatch schedules at MWPFs to be evenly distributed, while considering the revenue of MWPFs, even when the chosen date fell within the drought season. Furthermore, among the portfolio of mitigation resources, comprising SHPGs and BESS, the operation of SHPGs showed a high correlation with the forecast error that occurred in the ID phase.

In terms of revenue, the algorithm presented an opportunity to create a new stream of income for the owners of the renewable resource portfolio by utilizing the variability mitigation policy known as the incentive market, beyond traditional revenues from subsidies or conventional electricity sales. This implies that when applied in countries employing market-based measures for the mitigation of variability in renewable resources, the algorithm could promote system stability through voluntary participation by resource owners. Further, the algorithm demonstrated a reduction in GHG emissions that would have occurred in the absence of coordination, through the optimization process from a revenue perspective.

Typically, the life expectancy of SHPGs ranges from 30 to 70 years. Although initial investment costs might seem high compared to BESS, BESS has a shorter life expectancy around 15 years and is associated with environmentally hostile activities like mining, along with other concerns such as fire risks. Further, unlike BESS, SHPGs generate their own power through scheduling and can be installed anywhere a MWPF exists. Considering these advantages and the effectiveness of SHPGs confirmed through the simulation with the scheduling algorithm, future efforts should harness the advantages of SHPGs, as exemplified in this study.

In this study, we primarily incorporated factors related to water intake and dispatch such as water demand, storage, and utilization factor in relation to MWPF. However, a more in-depth consideration reveals that the operation of MWPF includes water treatment processes such as sludge separation, filtration, and disinfection of water resources. In future research, we plan to linearize these processes based on mixed integer linear programming and incorporate them into the optimization equation for a more precise scheduling of MWPF.

Author contribution statement

Jae Ho Lee: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the Data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Kyoung Hoon Kim, Yeon Ouk Chu, Jae Young Oh, Yong Tae Yoon: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Sung Joong Kim: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the BK21 FOUR program of the Education and Research Program for Future ICT Pioneers, Seoul National University in 2023. This work was also supported by the Seoul National University Electric Power Research Institute (SEPRI).

Appendix A

Table A.1
Nomenclature of the variable.

Symbol	Description
$c \in C$	Index of the DERs in Coordinated Operations Including the BESSs, WPGs, and PVs
$x \in X$	Index of the DERs in Independent Operations Including the PVs and the SHPGs
$h \in H$	Index of Time in the Second Stage with Hourly Granularity
$p \in P$	Index of the Dispatch Pumps at The Water Treatment Facility
H_x	Net Head of the SHPGs at DAM or Control Reservoirs and the Water Process Facility
FP^{σ}	Price for the Incentive of the Variability Control within the Range in KRW/kWh
π_A, π_B	The Error Tolerance Represented in Percentage by 6% and 8%
π_C	The Tolerance Ratio for Capacity Factor of the Major Generation Resources Eligible for Settlement of the Forecast Incentive

References

[1] G. Strbac, D. Pudjianto, M. Aunedi, D. Papadaskalopoulos, P. Djapic, Y. Ye, R. Moreira, H. Karimi, Y. Fan, Cost-effective decarbonization in a decentralized market: the benefits of using flexible technologies and resources, IEEE Power Energy Mag. 17 (2019) 25–36, https://doi.org/10.1109/mpe.2018.2885390.
[2] D.E. Gernaat, H.S. de Boer, V. Daioglou, S.G. Yalew, C. Müller, D.P. van Vuuren, Climate change impacts on renewable energy supply, Nat. Clim. Change 11 (2021) 119–125, https://doi.org/10.1038/s41558-020-00949-9.
[3] O.M. Babatunde, J.L. Munda, Y. Hamam, Power system flexibility: a Review, Energy Rep. 6 (2020) 101–106, https://doi.org/10.1016/j.egyr.2019.11.048.
[4] M.L. Kubik, P.J. Coker, C. Hunt, The role of conventional generation in managing variability, Energy Pol. 50 (2012) 253–261, https://doi.org/10.1016/j.enpol.2012.07.010.
[5] E. Heylen, F. Teng, G. Strbac, Challenges and opportunities of inertia estimation and forecasting in low-Inertia Power Systems, Renew. Sustain. Energy Rev. 147 (2021), 111176, https://doi.org/10.1016/j.rser.2021.111176.
[6] M. Beaudin, H. Zareipour, A. Schellenberglabe, W. Rosehart, Energy storage for mitigating the variability of Renewable Electricity Sources: an updated review, Energy Sustain. Develop. 14 (2010) 302–314, https://doi.org/10.1016/j.esd.2010.09.007.
[7] M. Jafari, A. Botterud, A. Sakti, Decarbonizing power systems: a critical review of the role of energy storage, Renew. Sustain. Energy Rev. 158 (2022), 112077, https://doi.org/10.1016/j.rser.2022.112077.
[8] W.-P. Schill, Electricity storage and the renewable energy transition, Joule 4 (2020) 2059–2064, https://doi.org/10.1016/j.joule.2020.07.022.
[9] M. Jafari, M. Korpås, A. Botterud, Power system decarbonization: impacts of energy storage duration and interannual renewables variability, Renew. Energy 156 (2020) 1171–1185, https://doi.org/10.1016/j.renene.2020.04.144.
[10] Z. Tang, Y. Liu, L. Wu, J. Liu, H. Gao, Reserve model of energy storage in day-Ahead Joint Energy and Reserve Markets: a stochastic UC solution, IEEE Trans. Smart Grid 12 (2021) 372–382, https://doi.org/10.1109/tsg.2020.3009114.
[11] K. Parker, P. Barooah, Determining Reserve Requirements for energy storage to manage demand-supply imbalance in power grids, in: 2018 IEEE Electronic Power Grid (eGrid), 2018, https://doi.org/10.1109/egrid.2018.8598686.
[12] J. Lee, H. Jo, Integrated da coordination of der considering reliability constraints for participation in the Renewable Energy Certificate Market in South Korea: a case study in a der complex, Appl. Sci. 11 (2021) 5553, https://doi.org/10.3390/app11125553.
[13] R. Ko, D. Kang, S.-K. Joo, Mixed integer quadratic programming based scheduling algorithms for day-ahead bidding and intra-day operation of Virtual Power Plant, Energies 12 (2019) 1410, https://doi.org/10.3390/en12081410.
[14] H. Wei, Y. Zhang, Y. Wang, W. Hua, R. Jing, Y. Zhou, Planning integrated energy systems coupling V2G as a flexible storage, Energy 239 (2022), 122215, https://doi.org/10.1016/j.energy.2021.122215.
[15] L. Gong, W. Cao, K. Liu, Y. Yu, J. Zhao, Demand responsive charging strategy of electric vehicles to mitigate the volatility of Renewable Energy Sources, Renew. Energy 156 (2020) 665–676, https://doi.org/10.1016/j.renene.2020.04.061.
[16] M. Zhang, Z. Zhen, N. Liu, H. Zhao, Y. Sun, C. Feng, F. Wang, Optimal graph structure based short-term solar PV power forecasting method considering surrounding spatio-temporal correlations, IEEE Trans. Ind. Appl. 59 (2023) 345–357.
[17] D. Markovics, M.J. Mayer, Comparison of machine learning methods for photovoltaic power forecasting based on Numerical Weather Prediction, Renew. Sustain. Energy Rev. 161 (2022), 112364.
[18] L. Wang, M. Mao, J. Xie, Z. Liao, H. Zhang, H. Li, Accurate solar PV power prediction interval method based on frequency-domain decomposition and LSTM model, Energy 262 (2023), 125592.
[19] J. Kong, S. Oh, B.O. Kang, J. Jung, Development of an incentive model for renewable energy resources using forecasting accuracy in South Korea, Energy Sci. Eng. 10 (2021) 3250–3266, https://doi.org/10.1002/ese3.1020.
[20] S. Goodarzi, H.N. Perera, D. Bunn, The impact of renewable energy forecast errors on imbalance volumes and electricity spot prices, Energy Pol. 134 (2019), 110827, https://doi.org/10.1016/j.enpol.2019.06.035.
[21] S.A. Qadir, H. Al-Motairi, F. Tahir, L. Al-Fagih, Incentives and strategies for financing the renewable energy transition: a review, Energy Rep. 7 (2021) 3590–3606, https://doi.org/10.1016/j.egyr.2021.06.041.
[22] S.E. Kim, J. Urpelainen, J. Yang, State policy and lobbying in a federal system: evidence from the production tax credit for Renewable Energy, 1998–2012, State Pol. Pol. Quar. 21 (2021) 1–30, https://doi.org/10.1177/1532440020918865.
[23] X. Li, L. Yao, D. Hui, Optimal Control and management of a large-scale battery energy storage system to mitigate fluctuation and intermittence of renewable generations, J. Moder. Power Sys. Clean Energy 4 (2016) 593–603, https://doi.org/10.1007/s40565-016-0247-y.
[24] J. Conzen, S. Lakshmipathy, A. Kapahi, S. Kraft, M. DiDomizio, Lithium ion battery energy storage systems (BESS) hazards, J. Loss Prev. Process. Ind. 81 (2023), 104932, https://doi.org/10.1016/j.jlp.2022.104932.
[25] Z. Zhang, X. Yang, Z. Wang, Z. Chen, Y. Zheng, Highly applicable small hydropower microgrid operation strategy and Control Technology, Energy Rep. 6 (2020) 3179–3191, https://doi.org/10.1016/j.egyr.2020.08.037.
[26] H.S. Moon, Y.G. Jin, Y.T. Yoon, S.W. Kim, Prequalification scheme of a distribution system operator for supporting wholesale market participation of a distributed energy resource aggregator, IEEE Access 9 (2021) 80434–80450, https://doi.org/10.1109/ACCESS.2021.3085002.
[27] S. Karimi, S. Kwon, Optimization-driven uncertainty forecasting: application to day-ahead commitment with renewable energy resources, Appl. Energy 326 (2022), 119929, https://doi.org/10.1016/j.apenergy.2022.119929.
[28] C.P. Gerba, Drinking water treatment, Environ. Microbiol. (2009) 531–538, https://doi.org/10.1016/b978-0-12-370519-8.00025-0.

[29] P.K. Swamee, A.K. Sharma, Gravity flow water distribution system design, J. Water Supply Res. Technol. - Aqua 49 (4) (2000) 169–179, https://doi.org/10.2166/aqua.2000.0015.
[30] A.C. Vincent Denis, P. Punys, Integration of small hydro turbines into existing water infrastructures, Hydropower - Prac. App. (2012), https://doi.org/10.5772/35251.
[31] M. Xie, X. Cheng, H. Cai, J. Wang, S. Liu, Q. Chen, X. Liu, A hydropower scheduling model to analyze the impacts from integrated wind and Solar Powers, Sustain. Energy Grids Networks 27 (2021), 100499, https://doi.org/10.1016/j.segan.2021.100499.
[32] K. Kumar, R.P. Saini, A review on operation and maintenance of Hydropower Plants, Sustain. Energy Technol. Assessments 49 (2022), 101704, https://doi.org/10.1016/j.seta.2021.101704.
[33] P. Tomczyk, M. Wiatkowski, Impact of a small hydropower plant on water quality dynamics in a diversion and natural river channel, J. Environ. Qual. 50 (2021) 1156–1170, https://doi.org/10.1002/jeq2.20274.
[34] B.P. Machado, Large hydropower plants of Brazil, Compreh. Renew. Energy (2012) 93–127, https://doi.org/10.1016/B978-0-08-087872-0.00607-7.
[35] National Grid, Electr. Sys. Oper. Forward Plan (2018). Technical annexe. [Online]. Available:.
[36] Ministry of Trade, Infrastructure and Energy of the Republic of Korea, 2020. Order for the Forecast Incentive. [Online]. Available: https://www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_seq_n=163324&bbs_cd_n=81.
[37] Australian Energy Market Commission, Rules For The Market Settlement [Online]. Available:, 2022 https://www.aemc.gov.au/rule-changes/access-pricing-and-incentive-arrangements-distributed-energy-resources.
[38] I. Mitra, D. Heinemann, A. Ramanan, M. Kaur, S.K. Sharma, S.K. Tripathy, A. Roy, Short-term PV power forecasting in India: recent developments and policy analysis, Int. J. Ener. Environ. Eng. 13 (2022) 515–540, https://doi.org/10.1007/s40095-021-00468-z.
[39] R.J.K. Gross, P.J. Heptonstall, A systematic review of the costs and impacts of integrating variable renewables into power grids, Nat. Energy 6 (2020) 72–83, https://doi.org/10.1038/s41560-020-00695-4.
[40] S. Pineda, J.M. Morales, T.K. Boomsma, Impact of forecast errors on expansion planning of power systems with a renewables target, Eur. J. Oper. Res. 248 (2016) 1113–1122, https://doi.org/10.1016/j.ejor.2015.08.011.
[41] L.M. de Siqueira, W. Peng, Control strategy to smooth wind power output using Battery Energy Storage System: a Review, J. Energy Storage 35 (2021), 102252, https://doi.org/10.1016/j.est.2021.102252.
[42] J. Choi, J.-I. Lee, I.-W. Lee, S.-W. Cha, Robust PV-Bess scheduling for a grid with incentive for forecast accuracy, IEEE Trans. Sustain. Energy 13 (1) (2022) 567–578, https://doi.org/10.1109/tste.2021.3120451.
[43] S.-J. Kwon, S.-E. Lee, J.-H. Lim, J. Choi, J. Kim, Performance and life degradation characteristics analysis of NCM lib for Bess, Electronics 7 (12) (2018) 406, https://doi.org/10.3390/electronics7120406.
[44] K. Mongird, V. Viswanathan, P. Balducci, J. Alam, V. Fotedar, V. Koritarov, B. Hadjerioua, Energy Storage Technology and Cost Characterization Report, 2019, https://doi.org/10.2172/1884043.
[45] M. Novak, T. Mozdren, R. Gono, M. Gono, Methods of small hydropower plants connection in Water Supply System. 2014, in: International Conference on Environment and Electrical Engineering, 2014, https://doi.org/10.1109/eeeic.2014.6835905.
[46] E. Gómez-Llanos, P. Durán-Barroso, J. Arias-Trujillo, J.M. Ceballos-Martínez, J.A. Torrecilla-Pinero, M. Candel-Pérez, Small and micro-hydropower plants location by using Geographic Information System, Environ. Green Techn. Eng. Int. Conf. (2018), https://doi.org/10.3390/proceedings2201300.
[47] H. Yoshioka, Mathematical modeling and computation of a dam–reservoir system balancing environmental management and Hydropower Generation, Energy Rep. 6 (2020) 51–54, https://doi.org/10.1016/j.egyr.2020.10.036.
[48] A.T. de Almeida, et al., Small-hydropower integration in a multi-purpose dam-bridge for sustainable urban mobility, Renew. Sustain. Energy Rev. (2011), https://doi.org/10.1016/j.rser.2011.07.047.
[49] H. Liu, G.B. Andresen, T. Brown, M. Greiner, A high-resolution hydro power time-series model for energy systems analysis: validated with Chinese hydro reservoirs, MethodsX 6 (2019) 1370–1378, https://doi.org/10.1016/j.mex.2019.05.024.
[50] P. Punys, L. Jurevičius, Assessment of hydropower potential in wastewater systems and application in a lowland country, Lithuania, Energies 15 (2022) 5173, https://doi.org/10.3390/en15145173.
[51] H. Beltran, R. Vidal, L. Basiero, J.M. Santos, J.A. Basiero, E. Belenguer, Micro hydro installation analysis in a wastewater treatment plant, Renew. Energy Power Qual. J. (2014) 15–20, https://doi.org/10.24084/repqj12.207.
[52] C. Bousquet, I. Samora, P. Manso, L. Rossi, P. Heller, A.J. Schleiss, Assessment of hydropower potential in wastewater systems and application to Switzerland, Renew. Energy 113 (2017) 64–73, https://doi.org/10.1016/j.renene.2017.05.062.
[53] GAMS Development Corporation, General Algebraic Modeling System (GAMS) Release 36.1.0, Fairfax, VA, USA, 2021.
[54] MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States.
[55] Korea Power, Exchange. (n.d, Retrieved April 27, 2023, from, https://new.kpx.or.kr/.
[56] H. Akoglu, User's guide to correlation coefficients, Turk. J. Emerg. Med. 18 (2018) 91–93.