Received: 21 January 2021 | Revised: 23 April 2022 | Accepted: 4 May 2022

DOI: 10.1049/gtd2.12506

IET Generation, Transmission & Distribution

ORIGINAL RESEARCH

Low-carbon generation expansion planning considering flexibility requirements for hosting wind energy

Mohammad-Amin Pourmoosavi | **Turaj Amraee**

School of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran

Correspondence
Turaj Amraee, School of Electrical Engineering, K.N. Toosi University of Technology, Tehran 16315-1355, Iran.
Email: amraee@kntu.ac.ir

Abstract

The operational flexibility of electric energy systems is one of the essential requirements for integrating a high share of renewable resources. The operational flexibility significantly impacts the mix of new power generation technologies. In this paper, a low-carbon generation expansion planning (GEP) model is presented to investigate the impacts of flexibility requirements of power systems with a high share of wind energy. An improved clustered unit commitment (CUC) formulation is proposed to capture the flexibility limitation of thermal generating units fully. In this regard, clustered 10-min ramp up/down limits for operational reserves, flexible-ramp reserves, and contingency reserves, are introduced. The yearly variations of load and renewable generations preserving the chronological time correlations are included, considering 36 representative days obtained by the clustering approach. Besides, two types of BES devices are considered to investigate the role of BES in the provision of flexibility. The proposed flexible low-carbon GEP model is formulated as a mixed-integer programming model, and an optimal expansion plan is obtained using the CPLEX algorithm. By incorporating improved CUC formulation into the low-carbon GEP model, more profound insight into power systems' flexibility requirement with high wind generation penetration is obtained.

1 | INTRODUCTION

1.1 | Generation expansion planning

Generation expansion planning is a power system study carried out to determine the optimal capacity-generation mix, including the numbers, capacity sizes, and installation times of new generating units to supply the load-energy demand over a long-term horizon. From the authors' point of view, all GEP studies can be divided into conventional GEP studies and modern GEP studies. This classification is based on the global concern about the environmental issues and transition of power sectors toward low-carbon, and required measures can be investigated in the modern GEP studies. In the modern GEP, renewable integration and low-carbon policies for a transition toward a low-carbon power sector are the main focus of the study.

In the conventional GEP studies, the main objective is to determine the future generation mix, i.e. the number, type, capacity size, and installation times of new generating units. Besides, In order to meet the forecasted load demand and energy over a long-term horizon, different technical and economic constraints such as power balance equilibrium, reserve requirements, and budget limits should be regarded [1, 2]. Mathematically the conventional GEP problem is formulated as an optimisation problem in which the objective function consists of different terms such as the investment cost of new generation units, the fuel cost of all generating units, operating costs, and maintenance costs. Additional constraints such as tunnel limits (the maximum allowable units that can be constructed each year), maximum yearly budget, reserve requirement, reliability constraints, power balance constraints, and other constraints can also be considered. In ref. [3] a multi-dimensional review of the GEP study is provided which interaction of GEP problem with different subjects, including transmission expansion planning, short-term operation of power systems, and energy policies are investigated. In ref. [4] a two-stage stochastic GEP model is presented which the retirement and rehabilitation of units are regarded as options for the planning and operation. The conditional value-at-risk is incorporated into the GEP model to model the rehabilitation cost and load forecast uncertainties. In ref. [5] a bi-level GEP model is presented to investigate the impacts of energy efficiency resources (i.e. efficiency power plant). In this regard, efficiency power plants are modelled as GEP model investors. In addition, the effect of a regulatory support scheme for encouraging investors is studied. In ref. [6] a stochastic GEP model is introduced in order to study the impacts of different sources of uncertainties in the electricity market. It is shown that by combining multiple sources of uncertainties, investment decisions differ considerably from the case these uncertainties are not considered (i.e. deterministic framework). Also, it is demonstrated that the results for the case of combining multiple uncertainty sources differ from the case of superimposing each uncertainty source. In conclusion, the importance of the proposed approach is emphasised. In ref. [7] a multi-year GEP model is proposed, which seeks to limit the water consumption of thermal power generation while planning the capacity-generation mix for Iran's power system. In this regard, selecting appropriate cooling systems for thermal units and utilising renewable resources are two main tools for the limitation of water resources. Besides, air pollution constraints are also considered. It is shown that considering the limitation on the available water resources in the expansion model will drastically save the water resources and, therefore, lead to environment-friendly expansion planning of the power sector. It is worth mentioning that aside from studies conducted in generation expansion and transmission expansion planning, some studies focused on planning a distribution system. For example in ref. [8], the planning of a greenfield distribution system is studied. The study seeks to obtain cost-efficient expansion plan while promoting the distribution system reliability. In this regard, different alternative planning models for a greenfield distribution system are investigated. It is suggested that using geometrical maps of the distribution system improves the analysis. It is emphasised that the distribution of loads along different sections of a distribution system is critical and, therefore, these aspects should be considered in the planning of the green field distribution system.

1.2 | Low-carbon GEP

Rapid climate change and global warming challenge the conventional GEP models. For the transition toward a low-carbon power sector, the main low-carbon tools are (1) deployment of renewable resources, 2) consideration of low-carbon policies, 3) utilisation of carbon capture, utilisation, and storage (CCUS) technology, (4) phase-out of generation units with high CO_2 emissions and (5) Improving the generation efficiency (e.g. improving the efficiency of coal-fired units and converting natural gas open-cycle to natural gas combined-cycle). Recent studies have addressed the GEP problem in the low-carbon framework. In ref. [9], a multi-stages long-term generation mix for the 2030 year in Korea is investigated. To this aim, uncertainties, including the budget of planning and reliability of the power system and CO_2 emissions, are considered. The study seeks to obtain a multi-year best generation mix of the Korean power system. Also, fuzzy set theory is used to capture the uncertainties, leading to a trade-off between optimum solution and uncertainties in future planning, resulting in a more flexible solution rather than too robust planning. It should be noted that the flexible expansion plans resulted in handling the uncertainties of the power system, and unmanageable conditions of the power system were prevented. In ref. [10] a comprehensive review of methodological approaches for the integration of renewable resources in the GEP problem is studied. All GEP models are classified into three categories: optimisation, general/partial equilibrium, and alternative models. Afterward, each approach's advantages, disadvantages, and applications are discussed. Finally, it is concluded that these approaches should be combined for obtaining more realistic planning. In ref. [11] the impacts of CCUS cost and revenue on the GEP problem are investigated. It is demonstrated that under hard carbon policies and carbon revenue, the CCUS technology can be beneficial. Besides, CCUS nuclear units and renewable resources are deployed to realise the low-carbon target. The generation expansion planning under the low-carbon economy in China has been investigated in ref. [12]. The authors deployed CCUS and renewable resources as low-carbon tools without considering the details of renewable resources. Also, different types of thermal power plants with and without CCUS technology have been considered. In ref. [13] the impacts of incentive low-carbon systems such as emission trade and carbon-tax on GEP problem under renewable resources are investigated. The low-carbon GEP is conducted in a deregulation market from the viewpoint of market shares and financial risk for generation companies. It was shown that the low-carbon policy and renewable integration impact the investment decisions by generation companies. In ref. [14], the impacts of carbon-tax and renewable in GEP problem are investigated considering the load and wind uncertainties. The uncertainties of load demand and wind power generations are handled using the Gaussian copula method. The renewable resources are integrated via the renewable portfolio standard policy, but no CCUS technology is considered. In ref. [15] a GEP model is presented to determine the generation mix subject to a given carbon emission target. Wind generation is utilised as a low-carbon tool, and the emission costs are added to the objective function. The wind generation uncertainty is considered using the Weibull probability function. In ref. [16] a novel solution approach is introduced for the linear GEP model in which tri-objective linear programming is converted into an equivalent bi-objective linear programming problem. In this regard, three objectives of the proposed GEP model, including maximisation of total power generation from both renewable and non-renewable resources, minimisation of the total cost, and minimisation of total carbon emission, are converted into two objectives including (1) maximisation of the ratio of total power generation to the total cost and (2) the maximisation of the ratio of the total power generation to the total carbon emission. With respect to the weighted sum approach, it shows that by using a new solution method, lower total cost and lower total carbon emission under the same total power generation are obtained. In ref. [17] a multi-stage stochastic generation–transmission expansion planning model (GEP-TEP model) is introduced in which different uncertainties of a future power system such as load demand, fuel prices, and greenhouse gas emissions are considered. In addition, sustainability policies, including noise pollution and social expectation, consider the power system social responsibilities. In ref. [18] a multi-stage GEP model is introduced which health damages corresponding to the power system expansion are incorporated. In addition to the investment costs, fixed and variable operating and maintenance costs, social damages of pollutant emissions such as carbon and methane are also included. It is concluded that a considerable investment in renewable resources is needed to reduce the health damages from the power sector effectively. In ref. [19] a GEP model with different low-carbon tools, including storage, carbon-capture, and different carbon policies, is proposed. Also, a generalised clustering approach is introduced to select representative weeks for the expansion planning studies. It is shown that when four representative weeks or more are selected, the proposed approach is effective in terms of total costs of the system. It is also concluded that net load peaks should be regarded for the selection of representative weeks. In ref. [20] a bi-level optimisation model is proposed for the hybrid generation and transmission expansion planning model considering the cost of emission. In ref. [21], a multi-year low-carbon GEP model is proposed for Iran's power system. In this regard, all the main low-carbon tools, including efficiency improvement, coal phase-out, integration of renewable resources, utilisation of CCUS technology, and different low-carbon policies, are studied. In addition to renewable integration, coal phase-out, CCUS-retrofit for existing coal units, and efficiency improvement tools substantially impact low-carbon transition. Besides, it is shown that both carbon-tax and carbon-cap policies should be considered to obtain a low-carbon expansion plan. In ref. [22], a novel simulation platform is presented to thoroughly study the presence of renewable resources in the power system, including energy planning, dynamics, and protection of the power system. The proposed simulation platform is based on a geographic information system (GIS) to capture the geographical disparity of renewable resources. It is discussed that by using the GIS, expansion planning of new power plants and simulation of supply-demand scenarios can be studied in more detail. Also, the presented simulation platform can lead to more realistic planning due to assessing the technical feasibility of different proposed projects. It should be noted that the simulation platform can incorporate different aspects of a power system, including transmission network, distribution level, protection studies, and others.

The main focus of the previously proposed low-carbon GEP models is to integrate renewable generation under low-carbon policies to satisfy the load and energy demands within the emission targets.

1.3 | Flexible low-carbon GEP

In the era of green energy, high penetration of renewable resources is inevitable, and many countries worldwide have started moving toward a 100% renewable energy goal according to their commitments to Renewable Portfolio Standard (RPS) policy. Due to the intermittent nature of renewable resources, their integration needs sufficient operational flexibility. Operational flexibility is defined as the ability of a power system to handle the variability (i.e. predictable changes) and uncertainty (i.e. unpredictable changes) in both generation and demand sides over different time horizons. The flexibility requirement can be provided using ramp up and down reserves from different resources such as conventional generating units and energy storage devices. On the other hand, the operational flexibility of the conventional generating units is affected by their technical characteristics such as ramp up and down rates, start-up and shut down limits, minimum up and down times, and their energy prices [23]. In ref. [24], different analytic frameworks are presented for assessing the operational flexibility of a power system. For obtaining a detailed evaluation of the power system flexibility, different indices and metrics are discussed. Additionally, different available approaches for improving the power system flexibility are presented. To achieve a comprehensive overview of power system flexibility, three main aspects, including approaches to characterising the flexibility, enhancement of flexibility, and time frames of flexibility studies, are discussed in ref. [24].

Conventionally, flexibility requirements such as maximum ramp-up and ramp-down limits of units, minimum up–down time of units, and upward–downward spinning reserve are only considered in the short-term studies such as operation and control of power systems. However, due to the high share of renewable resources in future modern power systems, operational flexibility should also be considered in the long-term GEP studies of a power system to capture the technical challenges of renewable resources. Without considering the operational flexibility, the obtained capacity-generation mix is not realistic, and therefore the operational flexibility of the power system should be considered with more detail in the modern GEP models.

From the power system operator's point of view, in order to determine the realistic hourly schedule of power plants, the following mathematical aspects should be taken into account:

- Modelling the production cost of generating units
- Modelling start-up and shut-down costs of units
- Modelling operational limits of thermal generating units
- Production simulation via unit commitment model

These requirements can be considered in more detail in a short-term operational study. However, for a long-term GEP study, simplified models and procedures should be considered. Since the simplified UC models are a significant part of operational flexibility in GEP studies, a brief explanation for the simplified flexible UC models is needed. Mathematically, the unit commitment (UC) problem determines the optimal scheduling of generating units of a power system to meet the electricity demand while considering the operational limits of these units and maintaining equilibrium and security of the power system. In the UC model, for an hourly schedule of units, binary variables are defined to determine generating units' on-off status. Also, continuous variables are defined for determining the power generation of units. Due to high computational complexity, in long-term GEP studies, clustered unit commitment (CUC) models have been utilised. Power plants are grouped into clusters in CUC models depending on the technology and related operational characteristics. As a result, binary commitment variables are replaced by integer commitment variables. Afterward, flexibility constraints, including minimum up–down time, min–max generation level, upward–downward ramping rates, and reserve requirements, are formulated based on these clusters.

Since different proposed CUC models are proposed in the literature, a brief review of such models should be discussed. In ref. [25] a CUC model is proposed for approximate UC for efficient operational flexibility modelling. In ref. [26] a CUC problem formulation is presented for investment planning models, with the emphasis on modelling different categories of reserve requirements. However, the proposed model is not performed for any case study. In refs. [27] and [28] formulations of CUC along with maintenance scheduling are proposed for the GEP model, in which integer variables representing groups of units are used instead of usual binary variables. In ref. [29] relaxed flexibility constraints, including ramping reserve, minimum output, and minimum online–offline, are integrated with the proposed GEP model by using continuous variables instead of binary variables. In ref. [30] a network-constrained CUC formulation is introduced for incorporating operational flexibility in the GEP model. In refs. [31]–[33] the importance and effectiveness of their proposed improved CUC formulations in GEP study is validated. In ref. [34] a convex relaxation of the UC problem maintaining the tightness and tractability is proposed to incorporate the operational flexibility of the power system in the GEP model. It is shown that the proposed convex relaxation model is very accurate. In ref. [35] a flexible and unified UC model considering transition times (i.e. transition from on to off status) is developed, which is suitable for long-term UC studies. In ref. [36] instead of typical energy-based UC formulations, semi-relaxed power-based UC models is incorporated into GEP study. It is shown that the power-based model can represent the flexibility capabilities of the system more accurately. Ref. [37], it is shown that classical CUC formulation fails to model flexibility requirements of each unit in clusters accurately, and it overestimates the individual unit's flexibility and therefore proposed additional constraints for CUC formulation to overcome this issue.

There are many studies in the literature in which flexible GEP is conducted. In ref. [38], the concept of flexibility for incorporating uncertainties into power system planning is studied quantitatively. A novel maximum-regret index is proposed to indicate the flexibility of a generation mix of a power system. It is discussed that reducing the maximum regret of a power system leads to the higher flexibility. In ref. [38], the flexibility of a generation mix refers to the ability of a power system to cope with different sources of uncertainties. Finally, this study seeks to obtain the higher flexibility of a power system by making a trade off between flexibility and the economy of a power system (e.g. production cost). In ref. [39], planning and installation of battery energy storage systems (BESS) are studied for flexibility improvement of the Cypriot power system and transition toward a low-carbon power system. In this regard, a sophisticated flexibility adequacy assessment platform is presented to investigate the flexibility indices. Also, more details about the FLEXITRANSORE project and an evaluation method for the costs and advantages of integrating innovation technologies (e.g. smart grid innovations) into the power system to enhance flexibility are discussed. It is concluded that BESS promotes the Cypriot power system flexibility and can be used as a reliable flexible resource. The research works in refs. [26] and [27] are among the first works in integrating the CUC model into the long-term GEP problem. In refs. [27] and [28], it is shown that for a single year GEP model with larger shares of renewable generation, a flexible generation mix is required, and neglecting flexibility constraints in long-term expansion planning studies, may misrepresent the actual cost and performance of a particular mix and result in sub-optimal capacity mixes. In ref. [29] a capacity expansion model considering storage technologies, carbon tax, and renewable penetration is developed for the northwestern grid of China. It is shown that the generation capacity mix for thermal units will change drastically by incorporating flexibility constraints under high renewable penetration. The proposed model has a very high computational burden, in which the annual simulation involves approximately 2.3 million linear variables. The flexibility constraints, including ramping reserve, minimum power generation limit, minimum up time, and minimum down time, are integrated into the static (single year) GEP model. In ref. [30] the flexibility constraints, including ramping reserve, minimum output, minimum up and down times for a single year (i.e. 8760-h), are integrated via a clustered UC model in the GEP study. The flexibility constraints, including ramping reserve, minimum power generation limit, minimum up and down times, are integrated into the static (single year) GEP model. In ref. [36] a novel power-based GEP model for a single year is proposed. By using semi-relaxed power-based UC models show that the power-based model more accurately represents the flexibility capabilities of power systems. Besides, a semi two-stage algorithm is proposed as the solution method. The proposed model determines the investment decisions of renewable resources, energy storage systems, and thermal units. Also, detailed ramp limits and reserve requirements are considered. Also, the impacts of energy storage on flexibility are discussed. It is shown that by using a power-based UC model for the GEP study, the system flexibility is modelled more accurately, and therefore future generation mix is more suitable. In ref. [40] operational flexibility of future generation portfolios under a high share of renewable resources is considered. Also, an energy storage system and flexible CO_2 capture technology are considered. In ref. [41] unit commitment formulation is included in the GEP model in order to study the impacts of renewable generation on expansion planning of the power system. In order to capture the variability of renewable resources, a novel approach is proposed to include the extreme days with higher and lower levels of the net load. As a result, the impacts of different representative days on the planning of the power system are investigated. In ref. [42] literature review of the modelling and implementation of flexible ramping products (FRPs) for enhancing power system operational flexibility is presented. Related topics, including the challenges of increased variability and uncertainty on power systems and different enhancing approaches, are studied. In ref. [43] two metrics are proposed to quantify the flexibility of generating units and the whole system in the context of low-carbon. Besides, to capture the intra-day, daily, and seasonal variations in load and wind generation that drive the need for flexibility, four typical weeks and the extreme week of the winter are considered the representative weeks of the year. In this regard, a clustered UC model is developed to consider the flexibility requirements of generating units. In ref. [44] a new methodology based on the probabilistic distribution of flexibility adequacy is proposed. In this regard, new probabilistic indices based on flexibility are proposed to associate two concepts of renewable resources curtailment and flexibility with determining the type of flexible resources needed for the future generation. Besides, different possible combinations of load demand and renewable scenarios are assumed to evaluate the flexible resources. Also, four flexible resources, including flexible generators, energy storage, heat storage, and electric boiler, are considered. In ref. [45] the impacts of operating reserve requirement on generation capacity investment with the consideration of large-scale integration of renewable resources is studied. Also, the impacts of different operating reserve strategies are investigated. It is shown that the operating reserves have a substantial impact on the generation mix and a significant increase in renewable integration costs. The proposed model is only performed on a greenfield conceptual test system, in which no pre-existing generation capacity is assumed. In ref. [46] a three-stage robust flexible GEP model is proposed for the Egyptian power system to investigate the UC formulation under the short-term and long-term uncertainties of renewable and load. Also, as a flexibility tool, a battery energy storage system is utilised. It is shown that neglecting the power system's flexibility requirements results in unreliable expansion planning. In ref. [47] a two-stage robust flexible GEP model is proposed to study the impacts of the short-term and long-term uncertainty of wind energy. Also, the correlations of different candidate wind sites are investigated. It is concluded that less available wind capacity will be obtained by considering the correlations of candidate wind sites. Also, the impacts of pumped hydro storage (PHS) and fast gas turbines as tools for mitigating short-term uncertainties are studied. In ref. [48] single year capacity expansion study is conducted to assess the importance of energy storage system in future power systems with high penetration of wind–solar resources. It is shown that the increase in penetration level of renewable resources and reduction in the current capital cost of energy storage devices will lead to the higher utilisation of storage units. Also, the connection between the cost of renewable resources and the higher utilisation of storage units is discussed. In [49] long-term flexible GEP model is proposed to determine the optimal capacity-generation mix and market clearing prices. In this regard, short-term daily operational constraints, two low-carbon policies, including carbon-cap and carbon pricing, are incorporated into long-term planning. In order to investigate the impacts of carbon policies, different scenarios are studied. It is concluded that open-cycle units participate in flexibility provision by imposing different carbon policies for CO_2 emissions. Besides, higher carbon emission prices and higher penetration of renewable resources lead to more installation and power production of combined-cycle units. In ref. [50], the concept of flexibility in the distribution system is promoted by distributed energy resources (DERs). It is discussed that the constrained connection, i.e. DER connection to the network with the possibility of curtailment, is attracted some European countries as an investment deferral option by collaboration between distribution system operator (DSO) and DER owners. It should be noted that the flexibility concept in this work refers to the modification of generation or consumption patterns for provision of ancillary service or maintaining a stable grid operation. Also, the authors in ref. [50] discuss that the concept of flexibility from DERs at the distribution level has been emerging recently. Additionally, procurement of flexibility for congestion management, and case studies of constrained connection of DERs for several countries, including the UK, France, Germany, and Japan, are studied.

1.4 | Research gap and contributions

The concept of modelling flexibility in the expansion planning studies still requires more efforts in order to avoid overestimation of the flexibility capability of power systems, as discussed in different previous studies such as refs. [36] and [37]. This paper seeks to improve the previously proposed clustered unit commitment formulations in the literature by introducing additional reserve constraints to the classical clustered unit commitment formulation. By deploying the proposed detailed CUC formulation, the impacts of high penetration of renewable energy on the GEP problem are investigated more deeply, and valuable insights are gained. It is shown that in comparison with classical CUC formulation, for incorporating a high share of renewable resources, different results, including different types and sizes of thermal generating units, are obtained. Additionally, due to the promising role of battery storage units in enhancing the integration of renewable resources, the impacts of two types of battery storage units on improving the flexible operation of power systems with high penetration of renewable resources is investigated.

Regarding these issues, the main contributions of this paper are summarised as follows.

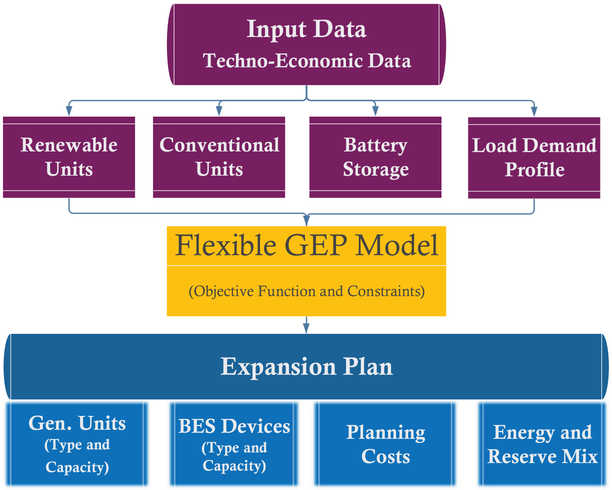

FIGURE 1 General structure of the proposed model

- Improving the previously proposed clustered unit commitment formulations in the literature by introducing additional reserve constraints to capture the operational limits of flexibility resources such as fast ramping thermal units, with an intra-hour resolution to fully capture the variability of wind generation, unlike many previous studies. Therefore deeper insight into future power systems' flexibility requirement with high penetration wind generation is obtained.
- Incorporating the proposed clustered unit commitment formulation into the proposed low-carbon GEP model in order to model the flexibility requirements of power systems with a high share of wind generation with more details
- Investigating the impacts of different types of energy storage units in the context of flexibility requirements of future power systems by using two different battery storage units with distinct characteristics

The rest of this paper is organised as follows. The formulation of the proposed flexible low-carbon GEP (FLC-GEP) model under the RPS scenario is proposed in Section 2. Also, the proposed improved CUC is introduced in Section 2.4. The simulation results of the proposed planning model over a comprehensive test case are given in Section 3. Finally, the paper is concluded in Section 4.

2 | FLEXIBLE GEP MODEL

This section presents the formulation of the proposed GEP model, including the objective function and related technical, economic, and carbon constraints. The general structure of the proposed model is illustrated in Figure 1.

2.1 | Objective function

The objective function including investment cost, generation cost, maintenance cost and carbon tax is represented in Equation (1) and different parts of total cost are defined in Equations (2)–(7).

$$C_{\mathrm{TOT}} = C_{\mathrm{I}}^{k} + C_{\mathrm{I}}^{b} + C_{\mathrm{OP}} + C_{\mathrm{OM}} + C_{\mathrm{OM}}^{b} + C_{\mathrm{tax}} \tag{1}$$

For the static flexible GEP study, only the total cost of the target year is considered, and to this aim, the concept of capital recovery factor (CRF) is used to convert the total investment to the yearly cost. The annualised investment cost of new conventional generating units and BES devices are represented by Equations (2) and (3) respectively. Other costs, including generation cost, maintenance cost, and carbon tax, are inherently calculated for the target year, and there is no need to use CRF for these costs.

$$C_{\mathrm{I}}^{k} = \sum_{i\in\Omega_g^k} \mathrm{CRF}_i\,(\nu_i\,\mathrm{Cap}_i)\,U_i \tag{2}$$

$$C_{\mathrm{I}}^{b} = \sum_{i\in\Omega_b} \mathrm{CRF}_i\,(\nu_i^{\mathrm{pc}}\,\bar{P}_i^{\mathrm{r}} + \nu_i^{\mathrm{s}}\,\bar{E}_i^{\mathrm{r}})\,U_i \tag{3}$$

The operational cost is given by Equation (4) and includes the cost of power generation and start-up costs of generating units.

$$C_{\mathrm{OP}} = \sum_{i\in\Omega_g}\sum_{d\in\Omega_d}\sum_{t\in\Omega_t} N_d\,(\rho_i\,\eta_i\,\mathrm{PG}_{i,d,t} + m_i^{\mathrm{su}}\,v_{i,d,t}) \tag{4}$$

The fixed and variable maintenance costs of generating units are represented by Equation (5).

$$C_{\mathrm{OM}} = \sum_{i\in\Omega_g^k} \mu_i^{f}\,\mathrm{Cap}_i\,U_i + \sum_{i\in\Omega_g}\sum_{d\in\Omega_d}\sum_{t\in\Omega_t} N_d\,\mu_i^{v}\,\mathrm{PG}_{i,d,t} \tag{5}$$

Also, the fixed and variable maintenance costs of BES devices are computed by Equation (6).

$$C_{\mathrm{OM}}^{b} = \sum_{i\in\Omega_b}\left\{\mu_i^{\mathrm{f}}\,\bar{P}_i^{r}\,U_i + \sum_{d\in\Omega_d}\sum_{t\in\Omega_t} N_d\,\mu_i^{v}\,(P_{i,d,t}^{\mathrm{ch}} + P_{i,d,t}^{\mathrm{dis}})\right\} \tag{6}$$

In order to reach the carbon target via the proposed GEP model, the carbon tax is calculated by Equation (7). According to Equation (7), the carbon tax depends on the total generated power and the carbon tax.

$$C_{\mathrm{tax}} = \sum_{i\in\Omega_g}\sum_{d\in\Omega_d}\sum_{t\in\Omega_t} [N_d\,\sigma\,\gamma_i\,\eta_i\,PG_{i,d,t}] \tag{7}$$

2.2 | Power balance constraints

The generation and load demand must be balanced at each hour of each day of the target year as given by Equation (8). Based on Equation (8), the sum of power generation of conventional units, renewable units, and storage charge/discharge

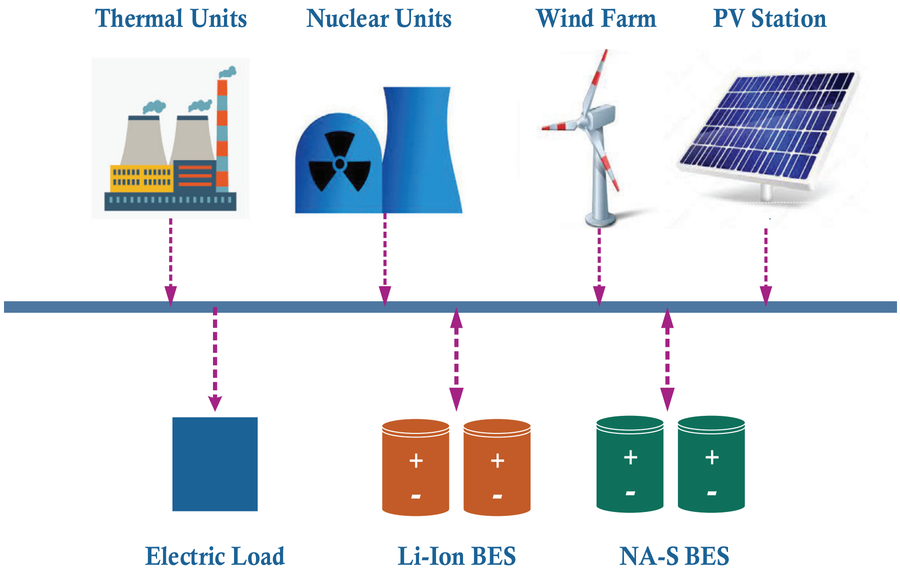

FIGURE 2 Different sources of power generation and load with storage devices

power must be equal to the load demand. The power balance concept is illustrated in Figure 2.

$$\sum_{i\in\Omega_g^{ex}} \mathrm{PG}_{i,d,t} + \sum_{i\in\Omega_g^{k}} \mathrm{PG}_{i,d,t} + \sum_{i\in\Omega_g^{s}} (\bar{P}^{s}_{i,d,t} - P^{\mathrm{curt}}_{i,d,t})$$

$$+ \sum_{i\in\Omega_b} (P^{\mathrm{dis}}_{i,d,t} - P^{\mathrm{ch}}_{i,d,t}) = \bar{L}_{d,t} \quad \forall d \in \Omega_d, \forall t \in \Omega_t \tag{8}$$

2.3 | Energy storage constraints

In this section, the formulations of ES devices are presented. Two different types of BES devices are considered, and each of these devices is installed for a specific goal. In this regard, Na-S BES devices are only used for energy arbitrage applications and cannot participate in the reserve schedule. Li-ion BES devices are used for both energy arbitrage and reserve scheduling applications. The constraint of Equation (9) defines the dynamics of the hourly energy state of each storage unit and relates every two consecutive energy states to the hourly charged or discharge power. According to Equation (10), the initial energy state of each ES unit must be equal to the final energy state. It should be noted that the constraint (10) ensures that ES units only contribute to the energy arbitrage (i.e. move the energy from low price to high price periods). The constraint (11) represents the minimum and maximum limits on the energy states of each ES unit.

$$E_{i,d,t} = (1 - B_{\mathrm{sd}})E_{i,d,t-1} + B_{\mathrm{e}}P^{\mathrm{ch}}_{i,d,t-1} - (1/B_{\mathrm{e}})P^{\mathrm{dis}}_{i,d,t-1}$$
$$\forall d \in \Omega_d, \quad \forall t \geq 2 \tag{9}$$

$$E_{i,d,t=0} = E_{i,d,t=24} = (1 - B_{\mathrm{dod}})\bar{E}^{r}_{i} U_i \tag{10}$$

$$(1 - B_{\mathrm{dod}})\bar{E}^{r}_{i} U_i \leq E_{i,d,t} \leq \bar{E}^{r}_{i} U_i \tag{11}$$

The maximum charge/discharge power of each ES unit is considered using Equations (12) and (13). Based on Equations (14) and (15), the simultaneous charge or discharge at each hour of the day is avoided. These two nonlinear constraints will be linearised before executing the MIP model.

$$P^{\mathrm{ch}}_{i,d,t} + r^{-}_{i,d,t} \leq \bar{P}^{\mathrm{r}}_{i} U_i \tag{12}$$

$$P^{\mathrm{dis}}_{i,d,t} + r^{+}_{i,d,t} \leq \bar{P}^{\mathrm{r}}_{i} U_i \tag{13}$$

$$P^{\mathrm{ch}}_{i,d,t} + r^{-}_{i,d,t} \leq \bar{P}^{\mathrm{r}}_{i} (U_i) B^{\mathrm{s}}_{i,d,t} \tag{14}$$

$$P^{\mathrm{dis}}_{i,d,t} + r^{+}_{i,d,t} \leq \bar{P}^{\mathrm{r}}_{i} U_i (1 - B^{\mathrm{s}}_{i,d,t}) \tag{15}$$

Finally, the constraints (16) and (17) ensure that realisation of scheduled upward/downward reserves remain within maximum and minimum limits.

$$(1 - B_{\mathrm{sd}})E_{i,d,t} - (1/B_{\mathrm{e}})(P^{\mathrm{dis}}_{i,d,t} + r^{+}_{i,d,t}) \geq 0 \tag{16}$$

$$(1 - B_{\mathrm{sd}})E_{i,d,t} + B_{\mathrm{e}}(P^{\mathrm{ch}}_{i,d,t} + r^{-}_{i,d,t}) \leq \bar{E}^{\mathrm{r}}_{i} U_i \tag{17}$$

2.4 | Clustered unit commitment formulation

2.4.1 | Classical clustered unit commitment

Unit commitment (UC) problem determines the optimal scheduling of power plants of a power system to meet the electricity demand while taking into account the operational constraints of the power plant units. Solving large-scale unit commitment problems are computationally demanding, and therefore, it is typically restricted to periods of 1 day to 1 week. In order to represent the flexibility constraints in the GEP study, an approximate clustered UC model is proposed. Power plants are grouped into clusters in the clustered UC model depending on the technology and related operational characteristics. As a result, binary commitment variables are replaced by integer commitment variables. Afterward, flexibility constraints, including minimum up/down times, min/max limits of generation level, upward/downward ramping rates, and reserve requirements, are formulated based on the generation technology or clustered units. Therefore, clustered UC problem formulation can be used in the proposed GEP model to reduce the computational complexities. This section introduces the MILP formulation of a CUC model as a prominent part of the FLC-GEP model. The proposed CUC consists of different constraints for generating units. The minimum power generation of conventional units is imposed by Equation (18). Equation (19) imposes a maximum level of generation for the units with a minimum up-time equal to or greater than 2 h. However, if the minimum up-time of the units is equal to 1 h, Equations (20) and (21) should be imposed.

$$P_i^{\min}(z_{i,d,t}) \le P_{i,d,t} - r^-_{i,d,t} \tag{18}$$

$$\begin{aligned} P_{i,d,t} + r^+_{i,d,t} &\le P_i^{\max}(z_{i,d,t} - v_{i,d,t} - \omega_{i,d,t+1}) \\ &+ (P_i^{\min} + \mathrm{SU}_i)v_{i,d,t} + (P_i^{\min} + \mathrm{SD}_i)\omega_{i,d,t+1} \end{aligned} \tag{19}$$

$$P_{i,d,t} + r^+_{i,d,t} \le P_i^{\max}(z_{i,d,t} - v_{i,d,t}) + (P_i^{\min} + \mathrm{SU}_i)\, v_{i,d,t} \tag{20}$$

$$P_{i,d,t} + r^+_{i,d,t} \le P_i^{\max}(z_{i,d,t} - \omega_{i,d,t+1}) + (P_i^{\min} + \mathrm{SD}_i)\,\omega_{i,d,t+1} \tag{21}$$

In order to model hourly upward/downward ramp limits of conventional units, Equations (22) and (23) are defined. Depending on the hourly transition state of units, including (1) no change in the number of online units, (2) start-up of new units, and (3) shut-down of all/part of existing units, the maximum hourly upward/downward ramp limits of units differ.

$$\begin{aligned} P_{i,d,t} - P_{i,d,t-1} + r^+_{i,d,t} &\le 60\mathrm{RU}_i(z_{i,d,t} - v_{i,d,t}) \\ &+ (P_i^{\min} + \mathrm{SU}_i)\, v_{i,d,t} + (-P_i^{\min})\omega_{i,d,t} \end{aligned} \tag{22}$$

$$\begin{aligned} P_{i,d,t-1} - P_{i,d,t} + r^-_{i,d,t} &\le 60\mathrm{RD}_i(z_{i,d,t} - v_{i,d,t}) \\ &+ (P_i^{\min} + \mathrm{SD}_i)\,\omega_{i,d,t} + (-P_i^{\min})\, v_{i,d,t} \end{aligned} \tag{23}$$

The state transition approach is utilised to preserve the tightness and compactness of the CUC model. State transition constraints are given in Equations (24)–(27). It should be noted that the constraints (25) and (26) represent the minimum down time of existing and new thermal units, respectively. Also, constraint (27) models the minimum up time of both existing

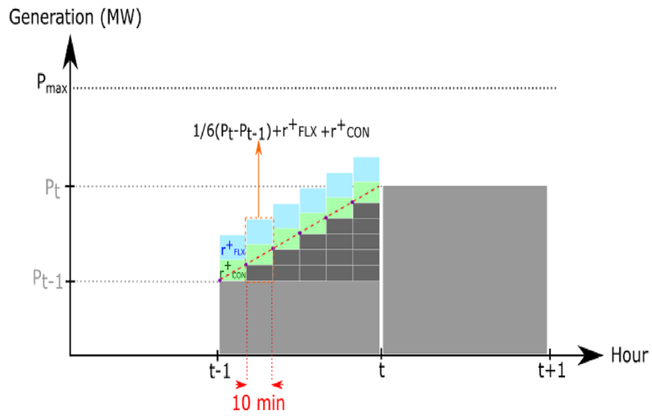

FIGURE 3 The Concept of 10-min ramp-up limit

and newly installed thermal units. For this study, the operating reserve includes contingency reserve and flexible-ramp reserve.

$$z_{i,d,t-1} - z_{i,d,t} + v_{i,d,t} - \omega_{i,d,t} = 0 \tag{24}$$

$$v_{i,d,t} \le N_i^{\mathrm{ex}} - z_{i,d,t-1} - \sum_{l \ge t+1-\mathrm{MDT}_i}^{l \le t-1} \omega_{i,d,l} \tag{25}$$

$$v_{i,d,t} \le U_i - z_{i,d,t-1} - \sum_{l \ge t+1-MDT_i}^{l \le t-1} \omega_{i,d,l} \tag{26}$$

$$\omega_{i,d,t} \le z_{i,d,t-1} - \sum_{l \ge t+1-MUT_i}^{l \le t-1} v_{i,d,l} \tag{27}$$

2.4.2 | Incorporating 10-min ramp up/down limits in classical clustered unit commitment

In order to improve classical CUC formulation, in this section novel 10-min reserve formulation is proposed. The classical CUC formulation improvement is achieved by considering more details of 10-min flexibility for each cluster. By considering the 10-min flexibility of each cluster, the overestimation of 1-h flexibility of clusters is avoided, and therefore more realistic scheduling for the flexibility requirements is imposed. The concept of 10-min ramp-up limit is illustrated in Figure 3.

The 10-min ramp up/down limits of units is imposed by Equations (28) and (29).

$$\begin{aligned} 1/6\,(P_{i,d,t} - P_{i,d,t-1}) + r^+_{i,d,t-1} &\le 10\mathrm{RU}_i\,(z_{i,d,t} - v_{i,d,t}) \\ &+ (1/6P_i^{\min} + 1/6\mathrm{SU}_i + 5/6(10\mathrm{RU}_i))v_{i,d,t} - 1/6P_i^{\min}\omega_{i,d,t} \end{aligned} \tag{28}$$

$$\begin{aligned} 1/6\,(P_{i,d,t-1} - P_{i,d,t}) + r^-_{i,d,t-1} &\le 10\mathrm{RD}_i\,(z_{i,d,t} - v_{i,d,t}) \\ &+ 1/6(P_i^{\min} + \mathrm{SD}_i)\omega_{i,d,t} + (5/6(10\mathrm{RU}_i) - 1/6P_i^{\min})v_{i,d,t} \end{aligned} \tag{29}$$

Constraints (31) ensure that by deploying both scheduled upward flexible-ramp and upward contingency reserves simultaneously in the first 10 min of each hour, the maximum generation level of conventional units is not violated. Also, Equation (33) ensures that by deploying both scheduled downward flexible-ramp and downward contingency reserves simultaneously in the first 10 min of each hour (in the case of an increase in generating power of renewable units), minimum generation level of conventional units is not violated.

$$P_{i,d,t-1} + 1/6\,(P_{i,d,t} - P_{i,d,t-1}) + r^{+}_{i,d,t-1}$$

$$\leq P^{\max}_{i}\,(z_{i,d,t} - v_{i,d,t}) + 5/6\,(P^{\min}_{i} + \mathrm{SD}_i)\,\omega_{i,d,t} \tag{30}$$

$$+(1/6P^{\min}_{i} + 1/6\mathrm{SU}_i + 5/6(10\mathrm{RU}_i))v_{i,d,t} \tag{31}$$

$$P_{i,d,t-1} + 1/6\,(P_{i,d,t} - P_{i,d,t-1}) - r^{-}_{i,d,t-1}$$

$$\geq P^{\min}_{i}\,(z_{i,d,t} - v_{i,d,t}) + 5/6\,(P^{\min}_{i})\,\omega_{i,d,t} \tag{32}$$

$$+\,(-5/6\,(10\mathrm{RU}_i) + 1/6\,P^{\min}_{i})\,v_{i,d,t} \tag{33}$$

Similar to the constraints proposed for the first 10-min of each hour, Equations (35)–(37) ensure that by deploying both scheduled upward/downward flexible-ramp and upward/downward contingency reserves in the last 10-min of each hour, maximum/minimum levels of generations of units is not violated.

$$P_{i,d,t-1} + 5/6\,(P_{i,d,t} - P_{i,d,t-1}) + r^{+}_{i,d,t-1}$$

$$\leq P^{\max}_{i}\,(z_{i,d,t} - v_{i,d,t}) + 1/6\,(P^{\min}_{i} + \mathrm{SD}_i)\,\omega_{i,d,t} \tag{34}$$

$$+\,(5/6\,P^{\min}_{i} + 5/6\,\mathrm{SU}_i + 1/6\,(10\mathrm{RU}_i))\,v_{i,d,t} \tag{35}$$

$$P_{i,d,t-1} + 5/6\,(P_{i,d,t} - P_{i,d,t-1}) - r^{-}_{i,d,t-1}$$

$$\geq P^{\min}_{i}\,(z_{i,d,t} - v_{i,d,t}) + 1/6\,(P^{\min}_{i})\,\omega_{i,d,t} \tag{36}$$

$$(-1/6\,(10\mathrm{RU}_i) + 5/6\,P^{\min}_{i})\,v_{i,d,t} \tag{37}$$

2.5 | Reserve formulations

To cope with the uncertainty of the actual generation of renewable resources and load demand, two different types of reserve scheduling are considered. This approach has been deployed in other works such as refs. [36], [29], and [43]. Based on Equations (38) and (39), the hourly upward/downward reserve of conventional units is a sum of upward/downward contingency and upward/downward flexible-ramp reserves of conventional units.

$$r^{+}_{i,d,t} = r^{\mathrm{Con}+}_{i,d,t} + r^{\mathrm{Flx}+}_{i,d,t} \tag{38}$$

$$r^{-}_{i,d,t} = r^{\mathrm{Con}-}_{i,d,t} + r^{\mathrm{Flx}-}_{i,d,t} \tag{39}$$

According to Equations (40) and (41), the contingency reserve is assumed as a certain percentage of hourly load to compensate for the generation outages. In order to handle the uncertainty of load and renewable generation, the flexible-ramp reserve is also incorporated as given in Equations (42) and (43). It is assumed that only online units can provide contingency reserves and flexible-ramp reserves.

$$\sum_{i\in\Omega_g} r^{\mathrm{Con}+}_{i,d,t} + \sum_{i\in\Omega_b} r^{\mathrm{Con}+}_{i,d,t} \geq C_{\mathrm{con}} \times \bar{L}_{d,t} \tag{40}$$

$$\sum_{i\in\Omega_g} r^{\mathrm{Con}-}_{i,d,t} + \sum_{i\in\Omega_b} r^{\mathrm{Con}-}_{i,d,t} \geq C_{\mathrm{con}} \times \bar{L}_{d,t} \tag{41}$$

$$\sum_{i\in\Omega_g} r^{\mathrm{Flx}+}_{i,d,t} + \sum_{i\in\Omega_b} r^{\mathrm{Flx}+}_{i,d,t} \geq C^{\mathrm{w}}_{\mathrm{Flx}} \bar{P}^{\mathrm{s}}_{w,d,t} + C^{\mathrm{l}}_{\mathrm{Flx}} \bar{L}_{d,t} \tag{42}$$

$$\sum_{i\in\Omega_g} r^{\mathrm{Flx}-}_{i,d,t} + \sum_{i\in\Omega_b} r^{\mathrm{Flx}-}_{i,d,t} \geq C^{\mathrm{w}}_{\mathrm{Flx}} \bar{P}^{\mathrm{s}}_{w,d,t} + C^{\mathrm{l}}_{\mathrm{Flx}} \bar{L}_{d,t} \tag{43}$$

3 | SIMULATION RESULTS

3.1 | Test case and assumptions

A large scale test system that is similar to the test systems used in refs. [7] and [21], with slight modification, is used. It should be noted that the assumed techno-economical parameters of existing and candidate units are chosen based on refs. [51]–[54]. Techno-economical parameters of existing units are given in Table 1. It is assumed that the total capacity of exiting units is 44,710 MW, and the peak load of the target planning year is assumed to be 90,000 MW. Techno-economical parameters of candidate units and BES devices are given in Tables 2 and 3, respectively. Two types of BES devices are considered, and each of these devices is installed for a specific objective. In this regard, Na-S BES devices are only used for energy arbitrage applications and cannot participate in the reserve schedule. Li-ion BES devices are used for both energy arbitrage and reserve scheduling applications. This assumption is based on the discharge times of candidate storage units, which for Na-S and Li-ion units, the discharge time is 6 h and 15 min, respectively. The operational characteristics of all thermal units are given in Table 4, that are mostly based on refs. [29] and [55]. In order to investigate the impacts of renewable resources on the flexibility of the power system, only wind power with high penetration is considered the main source of uncertainty and variability. For this study, the RPS policy is regarded, and it is assumed that the total capacity of wind units is increased to 50% of the peak load

TABLE 1 Techno-economic parameters of existing thermal generators

Fuel type	Technology	Capacity (MW)	Heat rate (Btu/kWh)	Existing Number	Fuel price($/MBtu)	Fixed O&M Cost($/kw-yr)	Variable O&M Cost($/MWh)	CO_2 Emission factor ($kgCO_2/MBtu$)
Nuclear	Steam	1020	11000	1	0.85	115	0.75	0
Coal	Steam	440	9247	17	1.45	71.5	4.3	95.52
Coal	Steam	320	9247	12	1.45	71.9	4.7	95.52
Coal	Steam	150	9247	11	1.45	72.3	5	95.52
Natural gas	Combined cycle	960	7667	10	3.45	5.7	3.2	53.06
Natural gas	Combined cycle	480	7667	14	3.45	6	3.5	53.06
Natural gas	Open cycle	320	10935	39	3.45	17.8	4.4	53.06
Natural gas	Open cycle	160	10935	12	3.45	18.1	4.7	53.06

TABLE 2 Techno-economic parameters of candidate units

Fuel type	Technology	Capacity (MW)	Heat rate (Btu/kWh)	Tunnel limit	Capital cost ($/kw)	Fuel price ($/MBtu)	Fixed O&M Cost($/kw-yr)	Variable O&M Cost($/MWh)	CO_2 Emission Factor ($kgCO_2/Btu$)
Nuclear	Steam	2200	10,460	3	6500	0.85	115	0.75	0
Natural gas	Steam	320	7754	25	6900	3.45	5.7	3.2	53.06
Natural gas	Steam	160	8124	25	7500	3.45	3.5	5	53.06
Natural gas	Combined cycle	960	6350	20	999	3.45	5.7	3.2	53.06
Natural gas	Combined cycle	480	6750	20	1200	3.45	6	3.5	53.06
Natural gas	Open cycle	320	8500	40	800	3.45	17.8	4.4	53.06
Natural gas	Open cycle	160	9600	40	950	3.45	18.1	4.7	53.06

TABLE 3 Techno-economic parameters of Storage units

Type	P_{max} (MW)	E_{max} (MWh)	Efficiency (%)	Variable OM ($/MW)	Fixed OM ($/kW-year)	Self discharge (%)	Tunnel limit	Life (years)	Power section Cost($/kw)	Storage section Cost($/kWh)	DOD (p.u)
Na-S	100	600	0.85	5	5	0	200	15	420	540	0.8
Li-ion	40	10	0.9	3.5	9	0	200	15	520	900	0.8

at the target planning year. In addition to the RPS policy, carbon tax policy is also regarded, which for the target year it is assumed to be 80 $\$/tCO_2$. Besides, the capacity factor of wind units is assumed to be 0.33, respectively. Under high penetration of renewable resources, in order to appropriately handle the daily net load, i.e. the remaining load that is not served by the renewable resources, these variations should be adequately examined on an hourly time scale. To model the uncertainties of renewable resources and load demand to some extent, representative days approach is deployed which different scenarios of normal monthly generation, one extreme scenario of monthly renewable actual generation, and one extreme scenario of monthly load demand are extracted using clustering approach, similar to other studies such as refs. [46], [47], [36], [43], [19], and [41]. To this end, to preserve the daily pattern of wind generation and load demand, 36 representative days for the target planning year are assumed. These 36 representative days are obtained by using a clustering approach [56]. According to the clustering approach, considering their correlations, a certain number of representative days are extracted for the load and renewable generation scenarios. As a result, 12-representative days based on yearly historical observation are obtained. In addition to these days, two additional days are selected for each month: the day containing the monthly peak load and the day with the highest wind generation. As a result, the 365 days of the target year are replaced with 36-days, including 12 typical days, 12 days with monthly peak load, and 12 days with the highest output of wind power. The result of representative days is shown in Figure 4.

Based on the proposed model defined in Section 2, the simulation results are presented in five different cases. In case 1, conventional GEP will be compared to two different flexible GEP models, i.e. simple and detailed flexible GEP. In conventional GEP, operational details are not considered and instead of proposed CUC formulation (18)–(43) only

TABLE 4 Operational characteristics of thermal units

Technology-fuel	Size (MW)	Min. output (p.u.)	1-h ramp up/down (p.u.)	Contingency-ramp up/down (p.u.)	10-Min flexible-ramp up/down (p.u.)	Minimum up/down Time (h)	Start-up Cost ($/MW)
Existing units							
ST-NUC	1020	0.8	0.1	0	0	24	200
ST-CL	440	0.5	0.3	0	0.15	12	147
ST-CL	320	0.5	0.3	0	0.15	10	147
ST-CL	150	0.5	0.3	0	0.15	8	147
CC-NG	960	0.3	0.5	0.5	0.25	6	88
CC-NG	480	0.3	0.5	0.5	0.25	5	88
OC-NG	320	0.3	0.7	0.7	0.5	1	88
OC-NG	160	0.3	0.7	0.7	0.5	1	88
Candidate units							
ST-NUC	2200	0.8	0.1	0	0	24	200
ST-NG	320	0.5	0.3	0	0.15	10	147
ST-NG	160	0.5	0.3	0	0.15	8	147
CC-NG	960	0.3	0.5	0.5	0.25	6	88
CC-NG	480	0.3	0.5	0.5	0.25	5	88
OC-NG	320	0.25	0.75	0.75	0.55	1	88
OC-NG	160	0.25	0.75	0.75	0.55	1	88

maximum/minimum generation level limits is imposed. Also, total cost includes investment cost, power generation cost(no start-up cost), maintenance cost, and carbon tax. It should be noted that, in case 1, BES devices are not considered. In case 2, the results of flexible co-planning of GEP and energy BES units are presented. In case 3, operating reserve impacts on flexible GEP are investigated. Two different values for the contingency reserve and two different values for the flexible-ramp reserve are considered. In case 4, the impacts of imposing 10-min limits including ramp up/down limits and feasibility check, i.e. constraints (28)–(37) will be studied. In case 5, the impacts of the investment cost of storage units will be investigated. Finally, In Section 3.7, the results are analysed in more depth. All proposed MIP models are solved by the CPLEX algorithm in GAMS software using an Intel Core i7 PC running at 3.6 GHz with 32 GB of RAM.

3.2 | Case 1: conventional GEP versus flexible GEP

In this case, the results of the conventional GEP model (CGEP) are compared with two flexible GEP models, i.e. simple flexible GEP (SFLGEP) and detailed flexible GEP (DFLGEP). The difference between simple and detailed flexible GEP models is that for DFLGEP, clustered UC formulation, i.e. Equations (18)–(43), is fully imposed. However, for SFLGEP, for clustered UC formulation, all constraints except 10-min ramp up/down limits a 10-min ramp up/down feasibility check constraints, i.e. constraints (28)–(37), are considered. According to Table 5, the difference between the total cost of the conventional GEP and two flexible GEP models is about 3.8 billion dollars. This result is mainly due to the difference in capital, start-up, and emission costs. Additionally, the total installed capacity obtained by two flexible GEP models is about 8 GW more than the conventional GEP model, which is shown in Figure 5. In this regard, more NGOC units are installed for two flexible GEP cases, that confirms the suitability of open cycle gas units in providing flexible ramping products. In addition, a 2200 MW nuclear unit is also installed for two flexible GEP cases mainly due to carbon-tax cost and lower fuel cost of NGOC units. Also, energy-mix for conventional GEP and flexible GEP models differs significantly, as can be seen in Figure 6. In this regard, for flexible GEP cases, NGCC units and steam units contribute less, and instead, NGOC units and nuclear units produce more energy with respect to the conventional GEP model. It should be noted that for two flexible GEP cases, more installation and more

TABLE 5 Comparative results for the expansion plans of case 1

	Models		
	CGEP	**SFLGEP**	**DFLGEP**
	Cost (billion $)		
Total ost	32.8	36.6	36.7
Capital ost	4.2	5.98	5.92
Fuel cost	11.06	11	11.1
Fixed O/M cost	3.4	3.7	3.7
Emission cost	14.2	13.4	13.5
Start-up cost		2.48	2.45

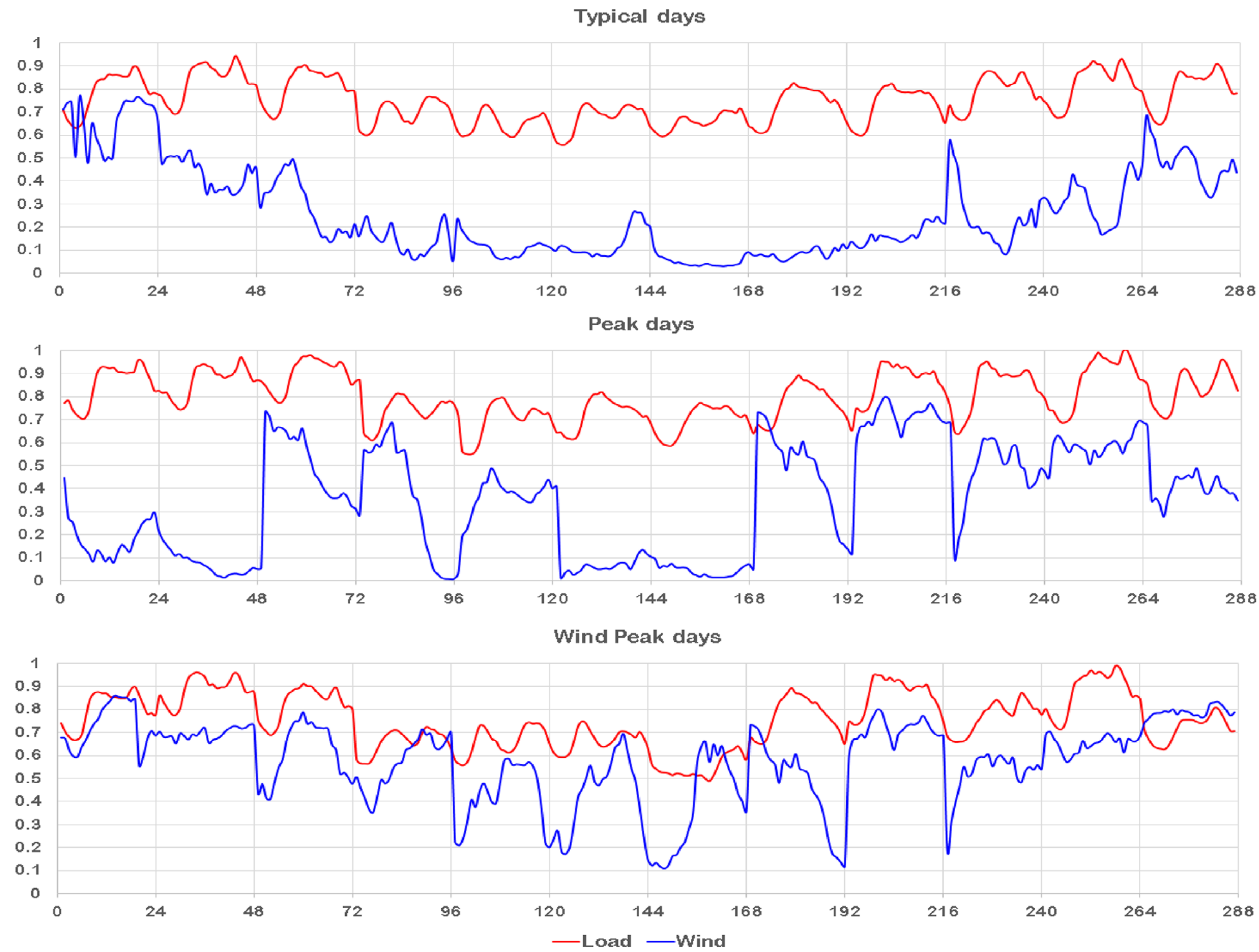

FIGURE 4 Hourly variations of representative days (p.u.)

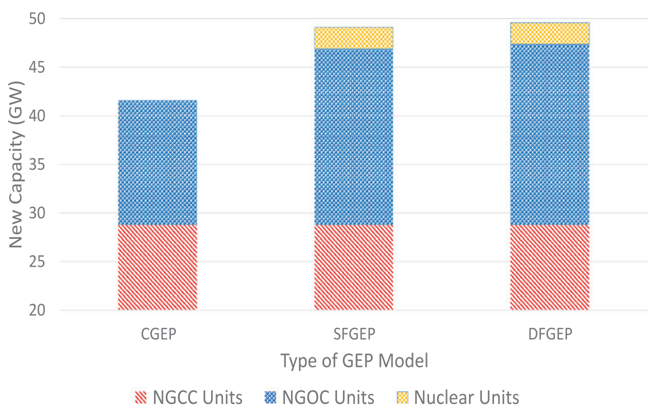

FIGURE 5 Capacity mix for the case 1

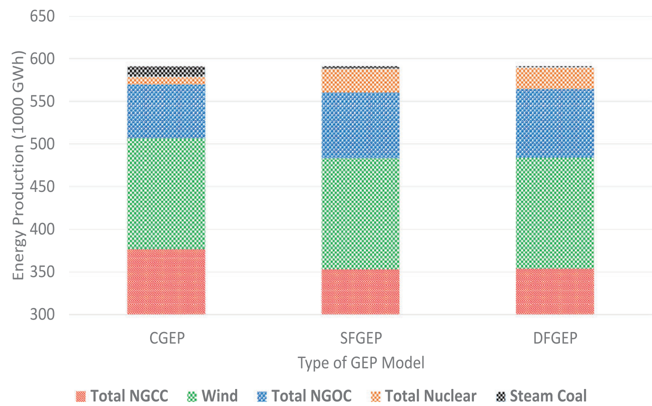

FIGURE 6 Energy mix for the case 1

energy production of NGOC units are due to the consideration of detailed operational requirements to balance the high share of wind units. It can be seen that less energy production of steam units in flexible GEP cases has led to less emission cost with respect to the conventional GEP. Due to more curtailment of wind generation in the flexible cases, the wind generation of conventional GEP is more than in the two other cases.

3.3 | Case 2: flexible GEP with BES co-planning

The results of flexible co-planning of generating units and the BES devices are discussed in this case. The impacts of battery ES devices on both simple flexible GEP and detailed flexible GEP models are investigated. According to Table 6, SFLGEP

TABLE 6 Comparative results for the case 2

	Models	
	SFLGEP	DFLGEP
	Cost (billion $)	
Total cost	36.48	36.7
Capital cost	5.9	5.32
Fuel cost	11.05	11.46
Fixed O/M cost	3.7	3.53
Emission cost	13.4	14.08
Start-up cost	2.45	2.3
	New installed capacity (GW)	
NGCC	28.8	28.8
NGOC	18.24	19.2
Nuclear	2.2	0
NG Steam	0	0
Storage units	0	2.76
Total capacity	49.24	50.76
	Total energy production (GWh)	
NGCC	353.24	360.32
Wind	129.90	129.96
NGOC	78.29	91.45
Nuclear	28	8.04
Steam	1.85	1.46

TABLE 7 Flexible-ramp reserve schedule forr the case 2

	Models	
	SFLGEP	DFLGEP
	Flexible-ramp reserve (p.u.)	
Total NGCC units	0.6	0.54
Total NGOC units	0.395	0.414
Total steam units	0.005	0.003
Storage units	0	0.043

has more investment cost but less fuel cost with respect to the DFLGEP. Also, the total cost of a detailed flexible GEP is slightly higher than the simple flexible GEP due to higher fuel costs and emission costs. From the perspective of the capacity mix, it can be seen that for DFLGEP, more NGOC units and more ES devices are installed. Also, in the SFLGEP, a 2200 MW nuclear unit is installed, which for the detailed flexible GEP, it is substituted with more NGOC and storage units. From the perspective of energy production, NGCC units contribute more to the detailed flexible GEP with respect to simple flexible GEP. Besides, more wind generation is attained due to more investment in storage units. Reserve-mix for two flexible GEP cases, i.e. upward flexible-ramp reserve, is given in Table 7. In the flexible-ramp reserve, NGCC units contribute less in the detailed flexible GEP, but NGOC units contribute more. Also,

TABLE 8 Comparative results for the case 3

	Operating reserve			
	Con: 3% load		Con: 5% load	
	Flx: 3% load+ 5% wind		Flx: 4% load+ 6% wind	
	Models			
	SFLGEP	DFLGEP	SFLGEP	DFLGEP
	New installed capacity (GW)			
NGCC	28.8	28.8	28.8	28.8
NGOC	17.92	18.4	18.24	19.2
Nuclear	0	0	2.2	0
NG steam	0	0	0	0
Storage units	0	0	0	2.76
Total capacity	46.72	47.2	49.24	50.76
	Total energy production (GWh)			
NGCC	363	362.5	353.24	360.32
Wind	130	130	129.90	129.96
NGOC	87.6	89.08	78.29	91.45
Nuclear	8.9	8.04	28	8.04
Steam	1.8	1.7	1.85	1.46
	Flexible-ramp reserve (p.u.)			
Total NGCC units	0.595	0.57	0.6	0.54
Total NGOC units	0.4	0.425	0.395	0.414
Total Steam units	0.005	0.005	0.005	0.003
Storage units	0	0	0	0.043

due to the investment of Li-ion BES units in DFLGEP, these units are scheduled as a flexible-ramp reserve. It should be noted that more contribution of NGOC and subsequently less contribution of NGCC units in the flexible-ramp reserve has resulted in more energy production of NGCC units. For the SFLGEP model, 60% of the flexible-ramp reserve is supplied by NGCC units, and both NGOC and steam units are scheduled for the remaining 40% of the required reserve. However, in DFLGEP, NGCC units are scheduled for 54% of the required reserve, and NGOC and steam units are scheduled for 41.7% of the flexible-ramp reserve.

3.4 | Case 3: impact of operating reserves

In this section, two different studies are considered to investigate the impacts of operating reserve on flexible GEP. According to Table 8, two different values of the contingency reserve, including 3% and 5% of hourly load forecast, are regarded. Also, two different values of the flexible-ramp reserve, including (a) 3% of hourly load forecast plus 5% of hourly wind forecast and (b) 4% of hourly load forecast plus 6% of hourly wind forecast, are considered. Regarding capacity mix, it can be seen that higher reserve requirement has led to more investment. More NGOC and BES units are installed for both simple and detailed flexible GEP cases. Also, a 2200 MW nuclear unit is installed in simple flexible GEP for higher reserve requirements. Regarding energy production, for higher reserve requirements, NGCC units produce less energy, and instead, NGOC and nuclear units together produce more energy in simple flexible GEP. However, for detailed flexible GEP, less energy production of NGCC units is substituted with more energy production of NGOC units. Also, higher reserve requirement results in more curtailment of wind units, which for detailed flexible GEP, this amount is minor than simple case due to more investment in BES units. From the perspective of the flexible-ramp reserve, higher reserve requirement has led to slightly less contribution of NGOC units. However, for higher reserve requirements, NGCC units contribute differently for two flexible cases. For higher reserve requirements, slightly more reserve is provided by NGCC units in simple flexible GEP, while less NGCC reserve is scheduled in detailed flexible GEP. These different trends for the flexible reserve of NGCC units can be explained by considering the reserve-mix, capacity-mix, and energy mix altogether: more investment of BES units in detailed flexible GEP with respect to simple case and lower energy production of NGCC units in detailed GEP case, i.e. from 362.5 to 360.32 GWh, together with result in less contribution of NGCC units in flexible-ramp scheduling. As a result, for detailed flexible GEP, under higher reserve requirements, NGCC, NGOC, and steam units contribute less, and instead, BES units are scheduled more.

3.5 | Case 4: impact of 10-min limits

In this section, the impacts of 10-min limits including ramp up/down limits and feasibility check, i.e. constraints (28)–(37) is discussed. According to Table 8, under higher reserve requirements, wind units generate more energy for detailed flexible GEP (129.96 GWh) with respect to simple flexible GEP (129.90 GWh). This result is mainly due to more NGOC and BES units investment, resulting in less renewable generation curtailment. Also, for flexible-ramp reserve, NGCC units are scheduled for 0.6 p.u. and 0.54 p.u. for simple flexible GEP and detailed flexible GEP, respectively. It can be seen that both NGCC and steam units contribute less in detailed flexible GEP, and instead, NGOC units are contributing more, i.e. from 0.395 p.u. in simple flexible case to 0.414 in detailed flexible GEP.

3.6 | Case 5: battery planning and reserve scheduling

In this case, the impacts of the investment cost of storage units on resulted generation expansion plan are discussed. In this case, Na-S BES devices are only used for energy arbitrage applications and are not allowed to participate in the reserve schedule. Li-ion BES devices are used for both energy arbitrage and reserve scheduling applications. Two different battery investment costs are considered, i.e. 0.8 p.u. and 0.6 p.u. of the original cost. The results of these cases for both simple and detailed flexible GEP models are given in Table 9. According to Table 9, by reducing the investment cost of storage units, the total installed capacity increases slightly, and more storage units are installed. In the simple flexible GEP, when the investment cost is reduced to 80% of the original cost, no Na-S BES unit is installed; when the investment cost is reduced to 60% of the original cost, 900 MW of Na-S unit, i.e. 37% of total BES capacity, is installed. In the detailed flexible GEP, the share of Na-S BES units is 20% and 12% of the capacity of installed storage under 80% and 60% investment costs, respectively. For these two cases, Li-ion units are installed more considerably with respect to the Na-S units, which shows the importance of the role of BES devices as a reserve resource. Also, it can be seen that much more BES is installed using a detailed flexible GEP model with respect to simple flexible GEP. When the investment cost of BES is assumed as 80% of the original cost, no storage is installed using simple flexible GEP, while 3.54 GW of BES devices is installed when the detailed flexible GEP is considered. This issue confirms the importance of the proposed detailed flexible GEP model. Also, 2200 MW installed nuclear unit in simple flexible GEP is substituted with more NGOC and BES units using detailed flexible GEP. When the investment cost of BES is assumed as 60% of the original cost, 2.46 GW BES units are installed using simple flexible GEP, while 4.22 GW BES units are installed using the detailed flexible GEP. The simulation result for the detailed flexible GEP model in the

TABLE 9 Comparative results for the case 5

	Battery investment cost			
	80%		**60%**	
	Models			
	SFLGEP	**DFLGEP**	**SFLGEP**	**DFLGEP**
	New installed capacity (GW)			
NGCC	28.8	28.8	28.8	28.8
NGOC	18.24	19.2	19.2	19.2
Nuclear	2.2	0	0	0
NG steam	0	0	0	0
Total storage units	0	3.54	2.46	4.22
Na-S units	0	0.7	0.9	0.5
Li-ion units	0	2.84	1.56	3.72
Total capacity	49.24	51.54	50.46	52.22
	Total energy production (GWh)			
NGCC	353.5	360.7	362	361.4
Wind	129.90	129.96	129.95	129.96
NGOC	78.06	90.5	88.9	90.2
Nuclear	27.9	8.04	8.9	8.04
Steam	1.9	1.98	2.1	1.72
	Flexible-ramp reserve (p.u.)			
Total NGCC units	0.596	0.52	0.506	0.502
Total NGOC units	0.397	0.394	0.44	0.376
Total steam units	0.007	0.007	0.006	0.005
Storage units	0	0.079	0.048	0.117

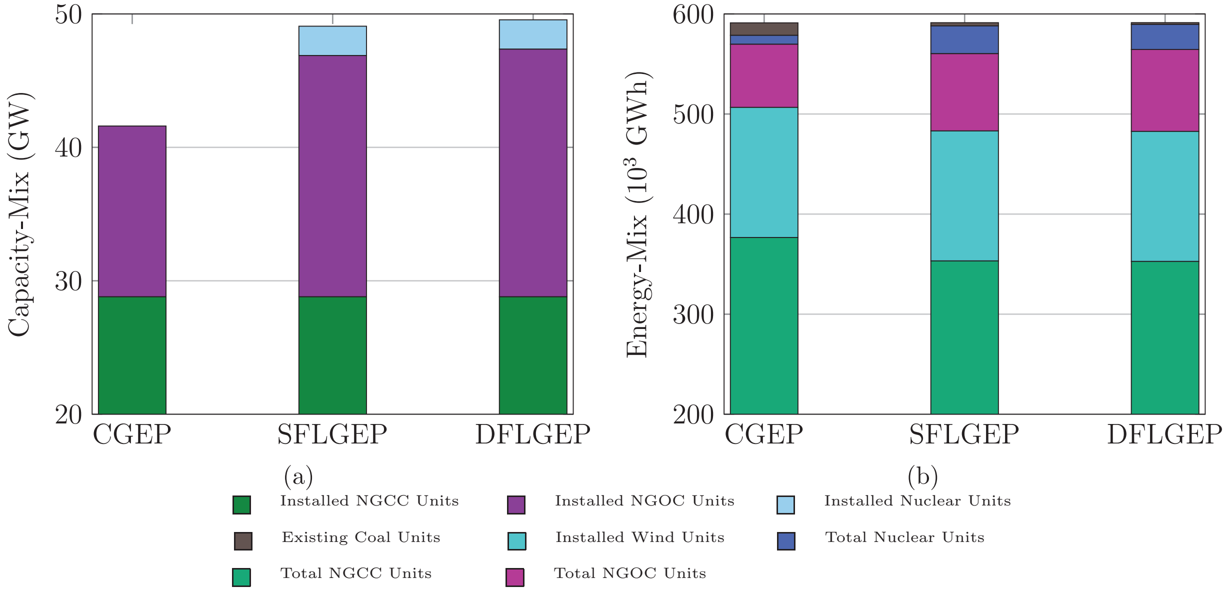

FIGURE 7 Result for the case 5 (0.6 p.u./DFLGEP)

case of reducing the BES investment cost to 60% of the original cost for six representative days is illustrated in Figure 7. For both prices (i.e. 80% and 60% of the original cost), more capacity is installed for detailed flexible GEP with respect to simple flexible GEP mainly due to more installation of BES units. With more installation of storage units, NGCC and NGOC units contribute less to flexible-ramp reserve, and instead, storage units contribute more. As a result, NGCC and NGOC units can produce more energy.

3.7 | Discussion

Based on the given simulation results of case 1 in Section 3.2, it is shown that in the conventional GEP, the total cost is underestimated mainly due to ignoring start-up costs. Also, regarding both flexible GEP models, less new capacity is installed. In addition, for conventional GEP energy mix is less sensitive to the variability of wind generation (i.e. less NGOC energy production), and therefore the obtained schedule is less likely to be realistic. It can be concluded that high detailed modelling of operational flexibility leads to a drastic change in capacity and generation mix.

Based on the given simulation results of case 2 in Section 3.3, the differences between simple and detailed flexible GEP models are as follows: (1) The total cost of detailed flexible GEP is slightly higher; therefore, the simple flexible GEP underestimates the expansion costs, (2) from a capacity-mix point of view, more NGOC units and ES devices are constructed in detailed flexible GEP, (3) from an energy-mix point's of view, higher energy is produced by NGCC and NGOC units in detailed flexible GEP, and (4) in reserve-mix point's of view, NGOC units contribute more, and NGCC and Steam units contribute less in flexible-reserve scheduling in detailed flexible GEP. Also, in detailed flexible GEP model, BES units are scheduled for 4.3% of the required flexible reserve.

Based on the results of case 3 in Section 3.4, imposing a higher reserve requirement has led to (1) more capital investment in notably Nuclear and NGOC units and ES devices, (2) Higher total energy production of NGOC and nuclear units together, and less energy production by NGCC, and more curtailment of wind energy, and (3) slightly less contribution of NGOC for flexible-ramp reserve.

Based on case 4 in Section 3.5, the impact of 10-min limits, i.e. the differences between simple and detailed flexible GEP models, are as follows: (1) The inclusion of 10-min limits can lead to more investment, mainly in new NGOC and BES units. (2) Capacity-mix of these two flexible cases can be different. For example, under higher reserve requirements, in detailed flexible GEP case, more NGOC and storage units are installed as a substitution for a 2200 MW nuclear unit in the simple GEP case. (3) In a detailed GEP case, NGCC and NGOC units produce more energy, and instead, nuclear and steam units produce less energy with respect to a simple, flexible GEP case. (4) More investment in NGOC and storage units for flexible GEP cases will lead to less curtailment of wind units. (5) For a detailed case, NGCC and steam units contribute less to flexible-ramp reserve, and instead, NGOC contributes more with respect to a simple case.

Based on the results of case 5 in Section 3.6, the impact of simple and detailed flexible GEP models on battery planning and reserve scheduling are as follows: (1) Much more BES is installed using a detailed flexible GEP model with respect to simple flexible GEP. With more installation of storage units, NGCC and NGOC units contribute less to flexible-ramp reserve, and instead, storage units contribute more. As a result, NGCC and NGOC units can produce more energy. (2) Using a detailed flexible GEP model leads to slight changes in capacity mix and energy mix, and reserve mix with respect to the simple flexible GEP. In other words, to obtain more realistic results for expansion planning, instead of using simple flexible GEP, a detailed flexible GEP model should be considered.

4 | CONCLUSION

This paper introduces a flexible low-carbon GEP model to co-optimise the generation expansion and energy-storage units under the high penetration of renewable resources. Also, in this paper, the carbon tax policy was used to facilitate wind integration and the impacts of other low-carbon policies. Five different case studies showed that the operational flexibility impacts the generation expansion plan significantly and avoids any underestimation/overestimation in required generation and BES capacity. As discussed in the first case study, by considering detailed flexibility constraints in the proposed long-term expansion planning model, a more realistic actual cost and generation mix is obtained, and sub-optimal capacity and generation mixes are avoided. The significant findings of this work are summarised as follows: (1) In order to model the operational details of the power system in the GEP model, the clustered unit commitment models enable the planners to consider the flexibility constraints, including minimum up/down times, upward/downward ramping rates and reserve requirements efficiently. (2) As discussed in the different case studies (cases 2–5), BES devices play an essential role in promoting operational flexibility. Two types of BES devices, including Na-S and Li-ion batteries, were considered. Na-S BES devices are only used for energy arbitrage applications, and Li-ion BES devices are used for energy arbitrage and reserve scheduling applications. It was shown that by using BES devices, a high share of wind power could be integrated with lower curtailment. Also, the need for expansion of thermal units is decreased. (3) As discussed in case study 5, by reducing the investment cost of BES units, Li-ion units are installed more than Na-S units, which illustrates the vital role of BES devices as a reserve resource and the energy arbitrage purposes. (4) As discussed in the different case studies (cases 2–5), it was shown that co-planning of generation expansion and ES units has led to different generation mixes, notably the substitution of the nuclear unit with more NGOC and storage units. (5) As discussed in case 4, By imposing 10-min constraints, more NGOC and storage units will be installed, and also they will contribute more to the flexible-ramp reserve. Future studies can investigate the impact of short-term uncertainty of wind and load demand over the assumed long-term horizon using stochastic or robust optimisation approaches.

NOMENCLATURE

i	Index for generating and storage units
t	Index for hours of each day
$k/s/b$	Index for types of candidate conventional/renewable/storage units
Ω_g	All existing and candidate conventional units
Ω_b	All candidate storage units
Ω_g^k/Ω_g^{ex}	All candidate/existing conventional units
Ω_t	All hours of each day of target year
Ω_d	All selected days of target year
Ω_g^s	All units of renewable portfolio
$\mathrm{MUT}_i/\mathrm{MDT}_i$	Minimum up/down time of clustered units i(h)
N_i^{ex}	Number of existing units i
CRF_i	Capital recovery factor of candidate unit i
SU_i	Start up rate of clustered units i(MW)
SD_i	Shut down rate of clustered units i(MW)
$\mathrm{RU}_i/\mathrm{RD}_i$	1-min ramp up/down rate of clustered units i (MW/min)
ν_i	Investment cost of candidate conventional unit i (\$/MW)
$\nu_i^{\mathrm{pc}}/\nu_i^{\mathrm{s}}$	Investment cost of power/storage section of candidate storage unit i (\$/MW/\$/MWh)
ρ_i/Cap_i	Fuel price/capacity of conventional unit i (\$/MBtu/MW)
η_i	Heat rate of conventional unit i (MBtu/MWh)
γ_i	Emission rate of conventional unit i ($t\mathrm{CO}_2$/MBtu)
σ	Carbon tax rate in the target year (\$/$t\mathrm{CO}_2$)
$\mu_i^{\mathrm{f}}/\mu_i^{\mathrm{v}}$	Fixed/variable maintenance cost of unit i (\$/MW-year/\$/MW)
m_i^{su}	Start-up cost of conventional unit i (\$/MW)
$\bar{P}_i^{\mathrm{r}}/\bar{E}_i^{\mathrm{r}}$	Rated power/energy of candidate storage unit i
N_d	Coefficient of each selected day d
$\bar{L}_{d,t}$	Forecasted demand (MW)
$P_i^{\min}$	Lower bound of power generation of unit i (MW)
$P_i^{\max}$	Upper bound of power generation of unit i (MW)
$\bar{P}_{i,d,t}^{\mathrm{s}}/\bar{P}_{w,d,t}^{\mathrm{s}}$	Forecasted generation of renewable unit i/wind units (MW)
C_{con}	Contingency reserve requirement coefficient for forecasted load demand (%)
$C_{\mathrm{Flx}}^{\mathrm{w}}/C_{Falx}^{\mathrm{l}}$	Flexible-ramp reserve requirement coefficient for forecasted wind generation/load demand (%)
$\mathrm{PG}_{i,d,t}$	Generation of conventional unit i (MW)
$P_{i,d,t}^{\mathrm{curt}}$	Curtailment of renewable unit i (MW)
$P_{i,d,t}^{\mathrm{ch}}/P_{i,d,t}^{\mathrm{dis}}$	Charged/discharged power of storage unit i (MW)
U_i	Number of new installed units
C_{TOT}	Total planning cost (\$)
C_I^k/C_I^b	Total investment cost of conventional/storage units (\$)
C_{OP}	Total generation cost of conventional units (\$)

C_{tax}	Total carbon emission tax of conventional units ($)
C_{OM}	Total maintenance cost of conventional units ($)
C^{b}_{OM}	Total maintenance cost of storage units ($)
$r^{+}_{i,d,t}/r^{-}_{i,d,t}$	Upward/downward reserve of clustered units i (MW)
$r^{\text{Con+}}_{i,d,t}/r^{\text{Con}-}_{i,d,t}$	Upward/downward contingency reserve of clustered units i (MW)
$r^{\text{Flex+}}_{i,d,t}/r^{\text{Flex}-}_{i,d,t}$	Upward/downward flexible-ramp reserve of clustered units i (MW)
$z_{i,d,t}/v_{i,d,t}/\omega_{i,d,t}$	Number of online/start-up/shut-down of clustered units i
$E_{i,d,t}$	Energy state of storage unit i (MWh)
$B^{s}_{i,d,t}$	Binary variable for the state of charge or discharge of storage unit i
$B_{\text{sd}}/B_{\text{e}}/B_{\text{dod}}$	Self-discharge/round-trip efficiency/depth of discharge of storage unit i (p.u.)

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Turaj Amraee https://orcid.org/0000-0002-5198-0067

REFERENCES

1. Majumdar, S., Chattopadhyay, D.: A model for integrated analysis of generation capacity expansion and financial planning. IEEE Trans. Power Syst. 14, 466–471 (1999)
2. Meza, J.L.C., Yildirim, M.B., Masud, A.S.M.: A model for the multiperiod multiobjective power generation expansion problem. IEEE Trans. Power Syst. 22, 871–878 (2007)
3. Koltsaklis, N.E., Dagoumas, A.S.: State-of-the-art generation expansion planning: a review. Appl. Energy 230, 563–589 (2018)
4. Farhoumandi, M., Aminifar, F., Shahidehpour, M.: Generation expansion planning considering the rehabilitation of aging generating units. IEEE Trans. Smart Grid 11, 3384–3393 (2020)
5. Ghaderi, A., Moghaddam, M.P., Sheikh El Eslami, M.: Energy efficiency resource modeling in generation expansion planning. Energy 68, 529–537 (2014)
6. Scott, I.J., Carvalho, P., Botterud, A., Silva, C.A.S.: Long-term uncertainties in generation expansion planning: implications for electricity market modelling and policy. Energy 227, 120371 (2021)
7. Pourmoosavi, M.A., Amraee, T., Firuzabad, M.F.: Expansion planning of generation technologies in electric energy systems under water use constraints with renewable resources. Sustain. Energy Technol. Assess. 43, 100828 (2021)
8. Hadjiionas, S., Oikonomou, D., Fotis, G., Vita, V., Ekonomou, L., Pavlatos, C.: Green field planning of distribution systems. In: Proceedings of the 11th WSEAS International Conference on Automatic Control, Modelling & Simulation (ACMOS'09), pp. 340–348. WSEAS, Athens (2009)
9. Jeong, S., Choi, J., Kim, J., Lee, Y., El Keib, A., Shahidehpour, M.: Flexible best generation mix for korea power system considering CO_2 constraint-vision 2030. In: 2008 IEEE Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1–6. IEEE, Piscataway (2008)
10. Dagoumas, A.S., Koltsaklis, N.E.: Review of models for integrating renewable energy in the generation expansion planning. Appl. Energy 242, 1573–1587 (2019)
11. Saboori, H., Hemmati, R.: Considering carbon capture and storage in electricity generation expansion planning. IEEE Trans. Sustain. Energy 7, 1371–1378 (2016)
12. Chen, Q., Kang, C., Xia, Q., Zhong, J.: Power generation expansion planning model towards low-carbon economy and its application in china. IEEE Trans. Power Syst. 25, 1117–1125 (2010)
13. Careri, F., Genesi, C., Marannino, P., Montagna, M., Rossi, S., Siviero, I.: Generation expansion planning in the age of green economy. IEEE Trans. Power Syst. 26, 2214–2223 (2011)
14. Park, H., Baldick, R.: Stochastic generation capacity expansion planning reducing greenhouse gas emissions. IEEE Trans. Power Syst. 30, 1026–1034 (2015)
15. Yuan, C., Gu, C., Li, F., Kuri, B., Dunn, R.W.: New problem formulation of emission constrained generation mix. IEEE Trans. Power Syst. 28, 4064–4071 (2013)
16. Chen, F., Huang, G., Fan, Y.: A linearization and parameterization approach to tri-objective linear programming problems for power generation expansion planning. Energy 87, 240–250 (2015)
17. Seddighi, A.H., Ahmadi Javid, A.: Integrated multiperiod power generation and transmission expansion planning with sustainability aspects in a stochastic environment. Energy 86, 9–18 (2015)
18. Rodgers, M.D., Coit, D.W., Felder, F.A., Carlton, A.: Generation expansion planning considering health and societal damages–a simulation-based optimization approach. Energy 164, 951–963 (2018)
19. Helistö, N., Kiviluoma, J., Reittu, H.: Selection of representative slices for generation expansion planning using regular decomposition. Energy 211, 118585 (2020)
20. Asgharian, V., Abdelaziz, M.M.A., Kamwa, I.: Multi-stage bi-level linear model for low carbon expansion planning of multi-area power systems. IET Gener. Transm. Distrib. 13, 9–20 (2019)
21. Pourmoosavi, M.A., Amraee, T.: Low carbon generation expansion planning with carbon capture technology and coal phase-out under renewable integration. Int. J. Electr. Power Energy Syst. 128, 106715 (2021)
22. Lazarou, S., Vita, V., Karampelas, P., Ekonomou, L.: A power system simulation platform for planning and evaluating distributed generation systems based on GIS. Energy Syst. 4, 379–391 (2013)
23. Nosair, H., Bouffard, F.: Flexibility envelopes for power system operational planning. IEEE Trans. Sustainable Energy 6, 800–809 (2015)
24. Mladenov, V., Chobanov, V., Zafeiropoulos, E., Vita, V.: Characterisation and evaluation of flexibility of electrical power system. In: 2018 10th Electrical Engineering Faculty Conference (BulEF), pp. 1–6. IEEE, Piscataway, NJ (2018)
25. Palmintier, B.S., Webster, M.D.: Heterogeneous unit clustering for efficient operational flexibility modeling. IEEE Trans. Power Syst. 29, 1089–1098 (2013)
26. Poncelet, K., van Stiphout, A., Delarue, E., D'haeseleer, W., Deconinck, G.: A clustered unit commitment problem formulation for integration in investment planning models. (2014). Accessed 12 December 2020
27. Palmintier, B.S.: Incorporating Operational Flexibility into Electric Generation Planning: Impacts and Methods for System Design and Policy Analysis. Massachusetts Institute of Technology, Cambridge (2013)
28. Palmintier, B.S., Webster, M.D.: Impact of operational flexibility on electricity generation planning with renewable and carbon targets. IEEE Trans. Sustain. Energy 7, 672–684 (2015)
29. Chen, X., Lv, J., McElroy, M.B., Han, X., Nielsen, C.P., Wen, J.: Power system capacity expansion under higher penetration of renewables with flexibility constraints and low carbon policies. IEEE Trans. Power Syst. 33, 6240–6253 (2018)
30. Du, E., Zhang, N., Kang, C., Xia, Q.: A high-efficiency network-constrained clustered unit commitment model for power system planning studies. IEEE Trans. Power Syst. 34(4), 2498–2508 (2018)
31. Meus, J., Poncelet, K., Delarue, E.: Applicability of a clustered unit commitment model in power system modeling. IEEE Trans. Power Syst. 33, 2195–2204 (2017)
32. Morales-España, G., Tejada-Arango, D.A.: Modelling the hidden flexibility of clustered unit commitment. IEEE Trans. Power Syst. 3(4), 3294–3296 (2019)
33. Du, E., Zhang, N., Kang, C., Xia, Q.: A high-efficiency network-constrained clustered unit commitment model for power system planning studies. IEEE Trans. Power Syst. 34, 2498–2508 (2019)

34. Hua, B., Baldick, R., Wang, J.: Representing operational flexibility in generation expansion planning through convex relaxation of unit commitment. IEEE Trans. Power Syst. 33, 2272–2281 (2017)
35. Zhang, L., Capuder, T., Mancarella, P.: Unified unit commitment formulation and fast multi-service lp model for flexibility evaluation in sustainable power systems. IEEE Trans. Sustain. Energy 7, 658–671 (2016)
36. Tejada Arango, D.A., Morales España, G., Wogrin, S., Centeno, E.: Power-based generation expansion planning for flexibility requirements. IEEE Trans. Power Syst. 35, 2012–2023 (2019)
37. Morales España, G., Tejada Arango, D.A.: Modeling the hidden flexibility of clustered unit commitment. IEEE Trans. Power Syst. 34, 3294–3296 (2019)
38. Nanahara, T., Takahashi, K., Nonaka, Y., Arakawa, F.: Approach to evaluation of flexibility of generation mix. IFAC Proc. Vol. 22, 157–162 (1989)
39. Vita, V., Christodoulou, C., Zafeiropoulos, I., Gonos, I., Asprou, M., Kyriakides, E.: Evaluating the flexibility benefits of smart grid innovations in transmission networks. Appl. Sci. 11, 10692 (2021)
40. Bruce, A.R., Gibbins, J., Harrison, G.P., Chalmers, H.: Operational flexibility of future generation portfolios using high spatial-and temporal-resolution wind data. IEEE Trans. Sustainable Energy 7, 697–707 (2015)
41. Yeganefar, A., Amin Naseri, M.R., Sheikh El Eslami, M.K.: Improvement of representative days selection in power system planning by incorporating the extreme days of the net load to take account of the variability and intermittency of renewable resources. Appl. Energy 272, 115224 (2020)
42. Wang, Q., Hodge, B.M.: Enhancing power system operational flexibility with flexible ramping products: a review. IEEE Trans. Ind. Inf. 13, 1652–1664 (2016)
43. Ma, J., Silva, V., Belhomme, R., Kirschen, D.S., Ochoa, L.F.: Evaluating and planning flexibility in sustainable power systems. IEEE Trans. Sustainable Energy 4, 200–209 (2013)
44. Lu, Z., Li, H., Qiao, Y.: Probabilistic flexibility evaluation for power system planning considering its association with renewable power curtailment. IEEE Trans. Power Syst. 33, 3285–3295 (2018)
45. van Stiphout, A., De Vos, K., Deconinck, G.: The impact of operating reserves on investment planning of renewable power systems. IEEE Trans. Power Syst. 32, 378–388 (2016)
46. Abdalla, O.H., Abu Adma, M.A., Ahmed, A.S.: Generation expansion planning considering unit commitment constraints and data-driven robust optimization under uncertainties. Int. Trans. Electr. Energy Syst. 31, e12878 (2021)
47. Abdalla, O.H., SMIEEE, L., Adma, M.A.A., Ahmed, A.S.: Two-stage robust generation expansion planning considering long-and short-term uncertainties of high share wind energy. Electr. Power Syst. Res. 189, 106618 (2020)
48. Mallapragada, D.S., Sepulveda, N.A., Jenkins, J.D.: Long-run system value of battery energy storage in future grids with increasing wind and solar generation. Appl. Energy 275, 115390 (2020)
49. Koltsaklis, N.E., Georgiadis, M.C.: A multi-period, multi-regional generation expansion planning model incorporating unit commitment constraints. Appl. Energy 158, 310–331 (2015)
50. Furusawa, K.: The fundamental evaluation of the methodology of constrained connection for distributed generation for procuring flexibility in european countries -lessons for Japan. In: CIGRE Canada Conference. IEEE, Piscataway, NJ (2019)
51. Lazard, N.: Lazard's levelized cost of energy analysis–version 13.0. https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf (2019). Accessed 12 December 2020
52. Mostafa, M.H., Aleem, S.H.A., Ali, S.G., Ali, Z.M., Abdelaziz, A.Y.: Techno-economic assessment of energy storage systems using annualized life cycle cost of storage (LCCOS) and levelized cost of energy (LCOE) metrics. J. Storage Mater. 29, 101345 (2020)
53. Rahman, M.M., Oni, A.O., Gemechu, E., Kumar, A.: Assessment of energy storage technologies: a review. Energy Convers. Manage. 223, 113295 (2020)
54. Mongird, K., Viswanathan, V.V., Balducci, P.J., Alam, M.J.E., Fotedar, V., Koritarov, V.S., et al.: Energy Storage Technology and Cost Characterization Report. Pacific Northwest National Lab. (PNNL), Richland, WA (2019)
55. Power System Flexibility for the Energy Transition, Part 1: Overview for Policy Makers, International Renewable Energy Agency, Masdar City (2018)
56. Krishnapuram, R., Keller, J.M.: A possibilistic approach to clustering. IEEE Trans. Fuzzy Syst. 1, 98–110 (1993)

How to cite this article: Pourmoosavi, M.-A., Amraee, T.: Low-carbon generation expansion planning considering flexibility requirements for hosting wind energy. IET Gener. Transm. Distrib. 16, 3153–3170 (2022). https://doi.org/10.1049/gtd2.12506