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Confronting the Duck Curve Problem Using Dynamic Economic Emission Dispatch with CAES

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Abstract: The high requirement for electrical energy, Photovoltaic (PV) installation price and environmental issues have led to PV installations' recent worldwide growth. The large PV penetration changes the daily load demands curve, especially on a sunny day, making a massive gap between load demands in the day and the night. This load demand curve shapes the duck curve both in the generation and the load demand side. In a duck curve, thermal generators' fuel costs and emissions are increased because their operation is not optimal, decreasing efficiency. In this study, compressed air energy storage (CAES) is added to the system for load demand balancing. The optimal dynamic economic emission dispatch (DEED) is performed to determine the best pattern of CAES operation and the optimal output of thermal generators to satisfy the 24-hour load demand for minimizing the fuel costs and emissions of the thermal generators simultaneously. The quadratic constrained programming is applied in this paper as the optimization tool for the DEED problem, and it is determined by using the CPLEX solver. Furthermore, the proposed model's feasibility is illustrated using different cases based on the IEEE 30-bus system. As a result, according to the comprehensive operational flexibility analyses, the proposed system is capable to handles the fast ramp of the duck curve, proved by no flexibility deficit in the planning periods. Finally, the thermal generators' fuel costs and emissions are also minimized. The total fuel cost was saved around $1180/day in case 1, $1970/day in case 2, and $3630/day in case 3, while the quantity of emissions was reduced by around 96.449 tons/day in case 1, 198.786 tons/day in case 2, and 351.193 tons/day for case 3.

Keywords: Duck curve, Large PV penetration, Dynamic economic emission dispatch, Compressed air energy storage, Operational flexibility.

1. Introduction

Currently, the increasing PV installations have been growing very fast worldwide because of the decline in PV installation costs and the general interest in green energy. The PV generations contribute to satisfying load demand and reducing fossil fuel-based thermal generators emissions. In 2020, more than 107 GW of PV additions reached at least 734 GW of the global cumulative installed PV capacity. China and the USA accounted for the world's most numerous PV installer countries, 40.4 GW and 16.7 GW, respectively [1, 2]. That PV global growth is an excellent achievement for the recent PV generation technology. Moreover, PV is extensively adopted because it has a broader range of availability and predictability than other renewable energy sources. As a result, PV has a high penetration rate. However, the high PV penetration changes the load generation and the load demand side.

The California independent systems operator in early 2013 released the chart, which shows the net load demand on a spring day by considering various PV penetration [3], as depicted in Fig. 1. The chart is duck-shaped, known as the duck curve. The curve shows a significant drop in load demand at the daytime as the electrical system is affected by massive PV penetration. Also, the chart depicts a loss of PV generation as the sun sets just as peak load demands begin in the early evening hours. This change in the demand curve raises concern that the thermal generators run into overgeneration, and the PV generation is curtailed.

Some studies have been proposed to investigate and determine strategies for reducing the duck curve impact on the operation of the power system. PV curtailment is one of the most common alternatives for solving the fast ramps of the duck curve. Curtailment lowers the power output of PV generation below its maximum capacity. As a result, the benefits of adding more PV may decline when additional installations are no longer cost-effective [4]. In [5], PV curtailment and energy storage utilization considering high PV penetration, have successfully reduced operating costs in a distribution system using techno-economic analysis but did not consider the duck curve effect. Besides, the proposed method could not increase the PV generation to the grid. In contrast, to keep the generator running and the ramping load satisfied economically, the percentage-based curtailment of wind and solar PV generation is applied in the power system operation, as shown in [6]. Although the duck curve can be reduced, the PV curtailment solution has not supported PV installation growth in the power system.

Moreover, due to the working time of PV, which generates electrical energy only during the day, the increasing PV penetration on the power system operation changes the load demand profile of the system. As a result, the difference between the load demand during the day and the night is extremely large, forming a duck curve that is commonly used to portray the imbalance load demand between off-peak and peak periods.

There are two shapes in the duck curve. The first one is the duck belly formed because, on the demand side, the PV is used as a primary power source during the day or off-peak periods, so the load demand in the power system is decreased. In this period, the larger the PV penetration, the fatter the belly. The second shape is the duck head formed because the PV generation is zero in the night or peak period, so the load demand is increased in this period. Therefore, load balancing is essential in a system with large PV penetration. The load balancing is the technical requirement for optimal scheduling of the thermal generator units [7]. Two types of research worked on load balancing to solve the duck curve problem: demand response and energy storage systems management.

The first is demand response. The CAISO proposed two ways to mitigate the duck curve effects: flattening and fattening the duck curve by implementing the demand response but did not consider the fast ramp of the duck curve [8]. In [9], electric vehicles demand scheduling with consider the load demand ramp-up, was proposed to flatten the duck curve. However, because the scheduling is only for electric vehicle charging stations, this method is difficult to implement in a large system with massive PV penetration. In [10], consumers' operating time is changed by implementing the incentives price of surplus electric energy has been proposed to suppress the ramp rate of the duck curve. This method uses a battery as an energy storage system but did not optimize its operation. In [11], a combination of distributed energy storage and demand response is proposed to flatten the duck curve. This proposed method uses the optimal dynamic pricing but did not consider optimal operation on the generation side.

Next, the researchers worked on load balancing using energy storage systems like super-capacitors, flywheel, superconducting magnetic energy, pumped storage hydroelectricity (PSH), batteries, and CAES. In [12], the flywheel has been proposed for balancing the load demand but did not consider the optimal dispatch of generator and flywheel. In contrast, electric PSH and boilers for heat [13] and PV forecasts and PSH [14] have been used to enable PV generations in smart grid and increase renewable source penetration but did not consider duck curve situations. In [15], considering the duck curve, the Whale Optimization Algorithm has been suggested for the size and placement of the battery energy storage system. The proposed method successfully minimized the system losses and can also be mitigated the duck curve issue. However, the method did not pay attention to the optimization of generators and batteries. Concentrated solar power (CSP) and PSH have been used for handling the duck curve problem [16]. The proposed method considers the optimal operation of generators and energy storage systems but did not consider the optimal emissions. Emissions are calculated but not optimized. In [17], the optimal design of PV installation was proposed to mitigate the duck curve problem with the unit commitment problem. However, it did not consider operational flexibility and the thermal generators' emissions. In [18], the energy management system has been implemented to handle the fast ramp of the duck curve. In this study, flexibility analysis is used for ramping evaluation. Besides, the proposed method also successfully minimized the operation cost of the system. However, this study did not consider the emissions of the thermal generator.

In this paper, CAES is used for load demand balancing with advantages: fast response, large capacity (storage and release), quick ramp-up process,

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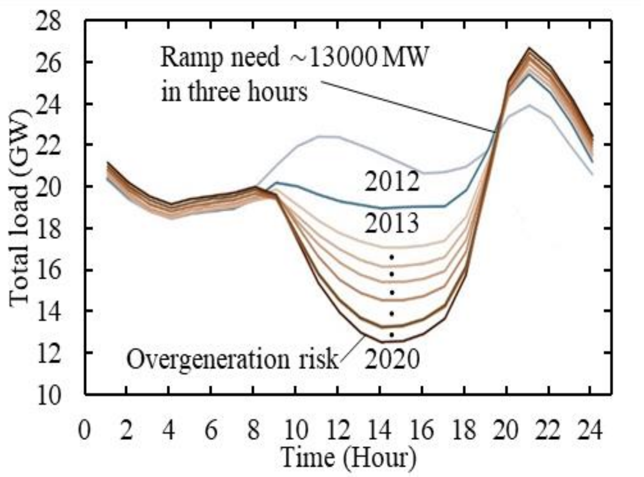

Figure. 1 The duck curve [3]

high efficiency, long life cycle, and low investment costs [19-24]. To eliminate a duck curve problem, CAES is compensating off-peak load and cutting peak load demand in power system operation. CAES uses surplus power in the system to drive the compressor for compressing the air and inject the compressed air into the storage. Conversely, CAES releases compressed air to drive the turbines, spinning a generator for generating electricity. CAES has been employed as an energy storage method in the system with wind power generation integrated [25]. The power system with wind power generation performance is improved when wind generation and CAES are combined. Furthermore, [26] has suggested multi-area economic dispatch using a probabilistic model that incorporates CAES and large wind power generating penetration. The proposed method successfully increases the capacity of spinning reserve while lowering operational costs.

Economic dispatch is essential for operating generators at the lowest cost in scheduling online thermal generators in a group in the power systems operation. There are two types of economic dispatch: static and dynamic. The static economic dispatch is used for minimizing the fuel cost of thermal generators in a defined independent period [27-31], whereas the dynamic economic dispatch (DED) aims for minimizing the fuel cost of thermal generators simultaneously under the changes in daily load demand [32-37]. The DED is more suited for actual power system operation in the optimum scheduling cycle since it can coordinate different power sources over some periods, not just calculating the lowest fuel cost.

DEED is the extended version of DED. DEED is a multi-objective constrained optimization problem of a group of online generators in operating power-generating systems. DEED has two objectives: minimizing generation costs and emissions subject to various constraints, including power balance constraints, the ramp rate of generator limits, and the capacity of generator constraints. Furthermore, the two objectives of DEED must be done simultaneously while the constraints are satisfied, which can be solved by scheduling the generators' output based on the load demands over a certain period.

In this research, DEED is used to determine the operation pattern of CAES, whether standby, generate, or save the electric power in a specific time by adding CAES constraints into the DEED calculation. Next, DEED finds the optimal thermal generator output to get the total minimum generation costs and emissions. In this paper, the CPLEX solver is used to solve the quadratically constrained programming on the DEED problem and implemented for solving the 24-hour dispatch problem in the IEEE 30-bus system to show the effectiveness of the proposed approach. Moreover, an operational flexibility analysis presents that the proposed method effectively solved the duck curve's fast ramps.

The rest of the paper is organized as follows. The problem formulation of the optimization work and the formulation of the proposed method are presented in section 2. Operational flexibility analysis is described in section 3. The case study is given in section 4. The simulation results and the comprehensive analysis are presented in section 5. Eventually, the conclusion is highlighted in section 6.

2. DEED with integration of CAES

The DEED has two aims: to minimize fuel costs and harmful emissions of thermal generators. The emission function is appended to the DED problem in the DEED problem, and it must deal with a multi-objective optimization technique that is more difficult than a one-objective optimization problem.

This research uses CAES to confront the duck curve problem in the electrical system. Depending on the power system's necessity. CAES can be worked as a load or generator. The operation of CAES was successful when the duck head was cut during peak load demand, and the duck belly was reduced during off-peak load demand.

Moreover, DEED has been used to specify the CAES operating pattern and the optimal output of thermal generators with several heavily restricted requirements, including power balance constraints, the capacity limit of thermal generators, the ramp rate limit of thermal generators, and CAES constraints.

2.1 The functions of thermal generator's fuel cost and emission

The first objective function of the DEED problem is to minimize the thermal generators' fuel cost in the dispatching cycle, which is represented as follows:

$$\min T_{FC}(t) = \sum_{t=1}^{NT}\left\{\sum_{i=1}^{NG}\left[\alpha_i P_i^2(t) + \beta_i P_i(t) + \gamma_i\right]\right\} \tag{1}$$

where

$T_{FC}(t)$ is the total fuel cost of thermal generators at the time t.

NT is the total dispatching period.

NG is the number of thermal generators.

$P_i(t)$ is the real power output of thermal generator unit i at time t.

$\alpha_i, \beta_i, \gamma_i$ are the fuel cost coefficients of thermal generators unit i.

The second objective function of the DEED problem is to reduce harmful emissions from fossil energy-based thermal generator units and can be stated as follows:

$$\min E(t) = \sum_{t=1}^{NT}\left\{\sum_{i=1}^{NG}\left[\delta_i P_i^2(t) + \varepsilon_i P_i(t) + \zeta_i\right]\right\} \tag{2}$$

where

$E(t)$ is the total emission of thermal generators at the time t.

$\delta_i, \varepsilon_i, \zeta_i$ are the emission coefficients of thermal generators unit i.

For the DEED problem, the emissions and total fuel cost need to minimize simultaneously. The comprehensive evaluation of a solution provided for the Pareto optimal front in the multi-objective optimization problem is achieved in this research using a fuzzy satisfying method [38]. This method works in the Pareto optimal front on the following principles: a membership function, μ, is defined for each solution, x^c. In minimizing the objective function k, the success degree of x^c is represented by μ value, which ranges from 0 to 1. For both objective functions, a linear membership function is implemented as follows:

$$\mu = \begin{cases} 0 & \text{Otherwise} \\ \dfrac{x_k^{max} - x_k^c}{x_k^{max} - x_k^{min}} & x_k^{min} \le x_k^c \le x_k^{max} \end{cases} \tag{3}$$

The final solution, ω, is as follows:

$$\omega = \max_{c=1:n}\left(\min_{k=1:2} \mu\right) \tag{4}$$

2.2 Constraints

In this research, the DEED must satisfy equality and inequality constraints. The following is a description of them.

2.2.1. Real power balance

All generating units' total outputs should be equal to the load demand. In this research, the CAES operation pattern is added to the power system in the real power balance. The CAES consumes real power ($-P_{com}$) from the power system for compressed air processing and generates real power ($\eta_{rel}P_{rel}$) for the power system. Mathematically, the real power balance can be expressed by:

$$P_D(t) = \sum_{i=1}^{NG} P_i(t) + \eta_{rel}P_{rel}(t) - P_{com}(t) \tag{5}$$

where

$P_D(t)$ is the load demand at t.

η_{rel} is the CAES compressed air release efficiency.

$P_{com}(t)$ is power for air compressing in CAES at t.

$P_{rel}(t)$ is power generated by CAES at t.

2.2.2. Capacity limit of thermal generators

The inequality constraints of the capacity limit of thermal generators can be expressed by:

$$P_i^{\min} \le P_i(t) \le P_i^{\max} \tag{6}$$

where $P_i^{\min}$ and $P_i^{\max}$ are the minimum and maximum power output of the ith thermal generator.

2.2.3. Ramp rate limit of thermal generators

Unlike the economic dispatch problem, the DEED problem has to satisfy the ramp rate constraints of thermal generators. In the DEED, thermal generators have a maximum ramp rate which limits their output change speed between time intervals, and it is expressed by:

$$P_i(t) - P_i(t-1) \le \mathrm{RUp}_i \tag{7}$$

$$P_i(t-1) - P_i(t) \le \mathrm{RDn}_i \tag{8}$$

where RUp_i and RDn_i are ramp-up and ramp-down

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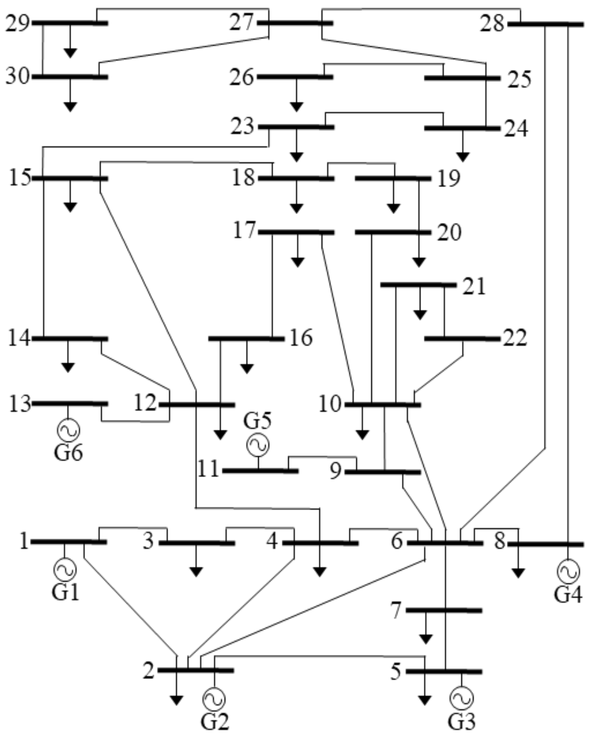

Figure. 2 IEEE 30-bus system

rate of the ith thermal generator.

2.2.4. CAES constraints

In this study, DEED is used for determining the optimal operation of CAES by implementing the constraints as follows:

$$V_C(t) = V_C(t-1) + (P_{com}(t)\eta_{com} - P_{rel}(t)/\eta_{rel})\Delta t \quad (9)$$

$$P_{com}^{\min} \leq P_{com}(t) \leq P_{com}^{\max} \quad (10)$$

$$P_{rel}^{\min} \leq P_{rel}(t) \leq P_{rel}^{\max} \quad (11)$$

$$V_C^{\min} \leq V_C(t) \leq V_C^{\max} \quad (12)$$

where

$V_C(t)$: Storage capacity of CAES at t.
$P_{com}^{\min}, P_{com}^{\max}$: CAES compressed air injection, minimum and maximum.
$P_{rel}^{\min}, P_{rel}^{\max}$: CAES compressed air release, minimum and maximum.
η_{com}: the compressed air injection efficiency in CAES
$V_C^{\min}, V_C^{\max}$: the minimum and maximum CAES storage capacity.

3. Operational flexibility analysis

The probability that the available power generation meets the load demand in a specific time scale without load shedding and curtailment is known as flexibility. There is downward and upward flexibility in the operational flexibility following the down-regulation and up-regulation. Insufficient downward flexibility results in renewable energy curtailment, while upward flexibility causes load shedding. The periods of flexibility deficit (PFD) [39] is used in this study and stated as follows:

$$P_U(t) = P_R(t) - F_P(t) \quad (13)$$

The load demand ramp is defined below:

$$P_R(t+1) = P_D(t+1) - P_D(t) \quad (14)$$

The capability of the power generation ramping in solving of the load demand ramps at t is known as available flexibility, and it is stated as follows:

$$F_P(t) = \sum_{i=1}^{NG} x_i(t)\min(\mathrm{RUp}_i, P_i^{max} - P_i(t)) \quad (15)$$

When the load demand ramp is negative:

$$P_U(t) = |P_R(t)| - F_P(t) \quad (16)$$

$$F_P(t) = \sum_{i=1}^{NG} x_i(t)\min\left(\mathrm{RDn}_i, P_i(t) - P_i^{min}\right) \quad (17)$$

where

$P_U(t)$: flexibility deficit at time t.
$P_R(t)$: load demand ramp at time t
$F_P(t)$: system flexibility at time t.
$x_i(t)$: on/off status of thermal generators unit i at time t.

4. Case study

In this section, an IEEE 30-bus system [40], which is presented in Fig. 2, is implemented to illustrate the proposed model. The system has 6 thermal generators, 21 loads, and 41 transmission lines. Table 1 shows the coefficients of the thermal generators cost functions. Table 2 presents the coefficients of the thermal generators' emission functions. Table 3 lists the thermal generators ramp rates. The CAES unit is located at bus 5. Table 4 presents the CAES specification with compress and release efficiency as follows: $\eta_{com} = 0.90$ and

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Table 1. Thermal generator cost coefficients in the IEEE 30-bus

Unit	α($/MW²)	β($/MW)	γ($)
G1	0.0612	33.0461	0
G2	0.2892	28.9153	0
G3	1.0327	16.5230	0
G4	0.1378	53.6999	0
G5	0.4131	49.5691	0
G6	0.4131	49.5691	0

Table 2. Thermal generators emissions coefficients in the IEEE 30-bus

Unit	δ(t/MW²)	ε(t/MW)	ζ(t)
G1	0.0126	-1.2000	22.983
G2	0.0200	-0.1000	25.313
G3	0.0270	-0.0100	25.505
G4	0.0291	-0.0050	24.900
G5	0.0290	-0.0040	24.700
G6	0.0271	-0.0055	25.300

Table 3. Power output constraints and thermal generators ramp rates in the IEEE 30-bus

Unit	$P^{\min}$ (MW)	$P^{\max}$ (MW)	RUp (MW/h)	RDn (MW/h)
G1	50	200	65	85
G2	20	80	12	22
G3	15	50	12	15
G4	10	35	8	16
G5	10	30	6	9
G6	12	40	8	16

Table 4. Specification of CAES

V_C^0 (MW)	$V_C^{\max}$ (MW)	$P_{inj}^{\min}$ (MW)	$P_{inj}^{\max}$ (MW)	$P_{rel}^{\min}$ (MW)	$P_{rel}^{\max}$ (MW)
50	500	5	50	5	50

Table 5. PV Locations and capacities in the IEEE 30-bus

Locations	Capacities (MW)		
	Case 1	Case 2	Case 3
bus 2, 5	67	92	115
bus 7, 8	31	43	54
bus 12, 19	27	37	47
bus 24, 30	26	35	44
Total	**151**	**208**	**260**

$\eta_{rel} = 0.95$.

The CPLEX solver [41] is implemented for solving the DEED problem. The average daily PV data [42] is implemented in this research under three different PV penetrations by changing the capacity of PV, as presented in Fig. 3, as follows:

Case 1: 28.09% PV penetration of peak load (151 MW PV capacity).

Case 2: 38.68% PV penetration of peak load (208 MW PV capacity).

Case 3: 48.35% PV penetration of peak load (260 MW PV capacity).

The locations and capacities of PV are spread into four areas, as listed in Table 5. The duck curve shape is formed by PVs at the load demand curve, as depicted in Fig. 4.

5. Simulation results

5.1 Solving DEED problem

The large penetration of PV leads to a duck curve problem, which reduces the thermal generators' efficiency and increases the thermal generators' fuel costs. CAES as a load balancer is implemented in this research to alleviate the duck curve problem caused by the massive load demand gap between peak and off-peak periods.

After the DEED simulation is run, Fig. 5 presents the optimallly schedulled power of CAES at every 1-hour step of the 24-hour dispatch periods. As can be seen, the CAES unit is switched into compressing/releasing modes during the operation period. CAES is compressing air then store the compressed air into the storage using the surplus load demand and CAES is releasing air compressed from the storage to the further processing for converted to the electrical energy. The CAES in case 3 is applied more than case 1 and case 2.

Also, as can be seen in Fig. 6 the highest CAES storage level is 94.29% occurs in case 3.

Fig. 7 shows the optimal power output of six thermal generators before considering CAES. As can be seen, the duck curve of the generators side is formed by the duck curve at the demand side. The duck curve belly size is due to the PV penetration.

Fig. 8 presents the optimum output of six thermal generators after considering CAES. Herein, the thermal generators are smooth in their operation.

Fig. 9 presents the comparation of the active power output of the thermal generators without considering CAES and with considering CAES. As can be seen, CAES changes the duck curve shape by cut the head and reduces the belly of the duck curve.

Fig. 10 ilustrates comparison of the total thermal generators fuel costs between DEED without considering CAES and DEED with CAES. The total fuel costs output by DEED with considering CAES in case 1 is $317390, case 2 is $299400 and case 3 is $283320 while for the DEED does not considering CAES the total fuel costs for case 1 is $318570, for case 2 is $301370 and for case 3 is $286950.

In accordance with the main purpose of DEED, namely to find the best compromised solution for both the thermal generators fuel costs and emissions.

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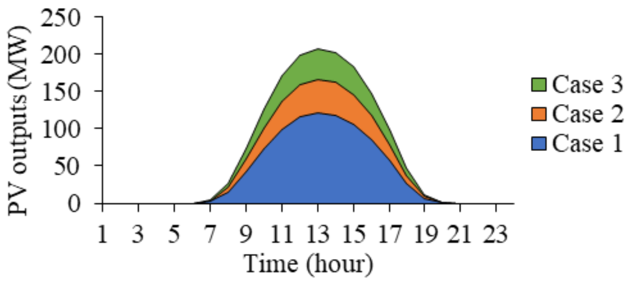


Figure. 3 Forecasted PV curves

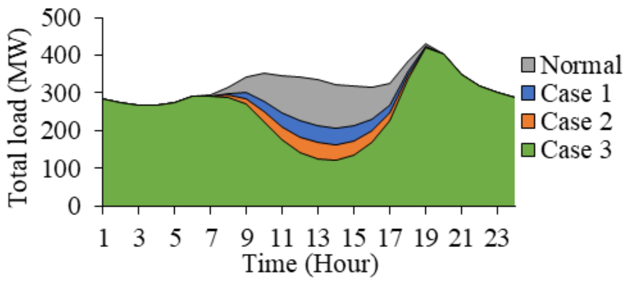
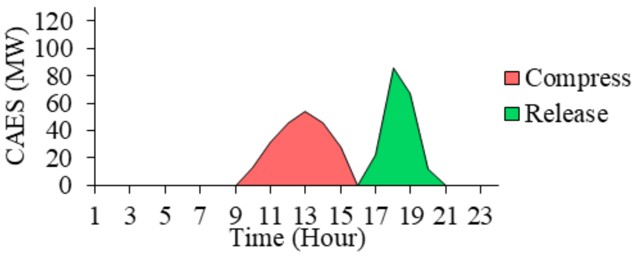
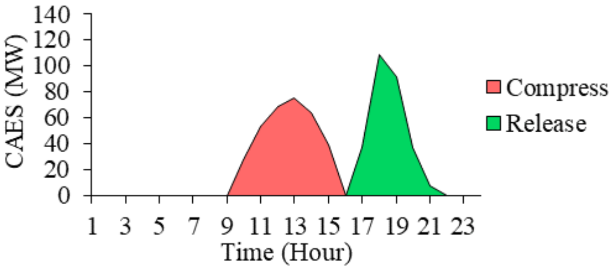


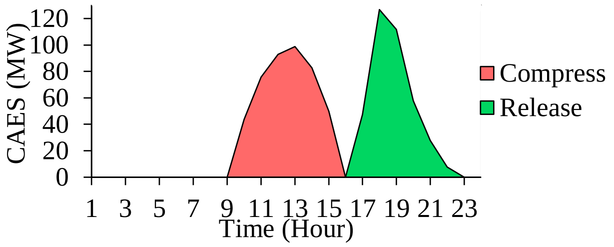
Figure. 4 Hourly demand loads



(a)



(b)



(c)

Figure. 5 Optimal operations of CAES: (a) Case 1, (b) Case 2, and (c) Case 3

Fig. 11 shows the thermal generators' emissions for the DEED without considering CAES and DEED with CAES. The total emissions produced by the thermal generator after considering CAES are 8444.627 tons for case 1, 7873.557 tons for case 2, and 7403.654 tons

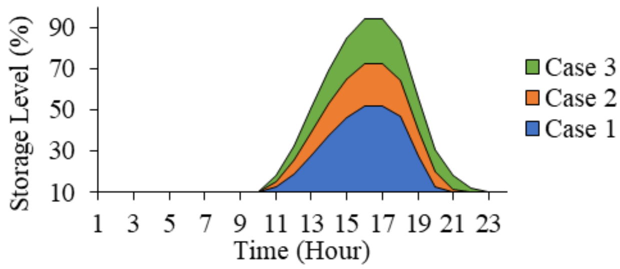
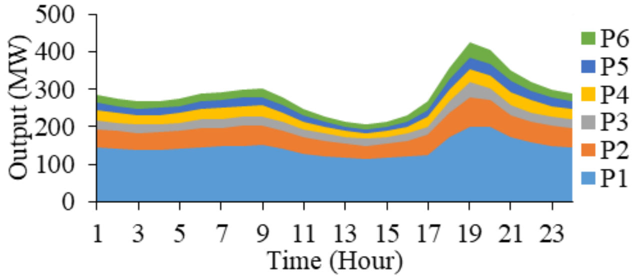
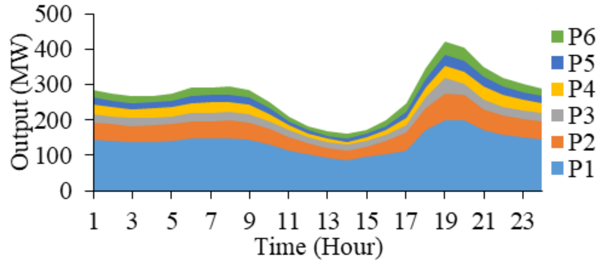


Figure. 6 Storage level of CAES



(a)



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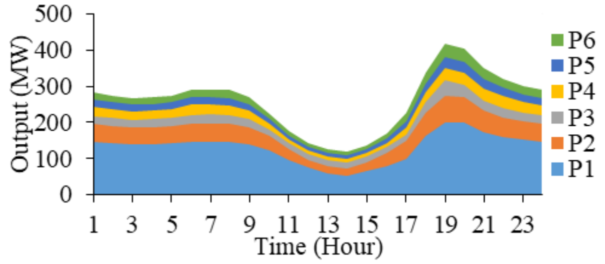

(c)

Figure. 7 Thermal generators output without CAES: (a) Case 1, (b) Case 2, and (c) Case 3

for case 3, meanwhile 8541.076 tons for case 1, 8072.343 tons for case 2, and 7754.847 tons for case 3 in the system before considering CAES.

The proposed method successful in reducing the total fuel costs and the emissions of thermal generators. The total fuel costs by $1180 in case 1, $1970 in case 2 and $3630 in case 3 while the emissions by 96.449 tons in case 1, 198.786 tons in case 2 and 351.193 tons for case 3.

5.2. Operational flexibility analysis

In this research, the effectiveness of the thermal generator units' and CAES' operational flexibility in solving the duck curve fast ramps is carried out using

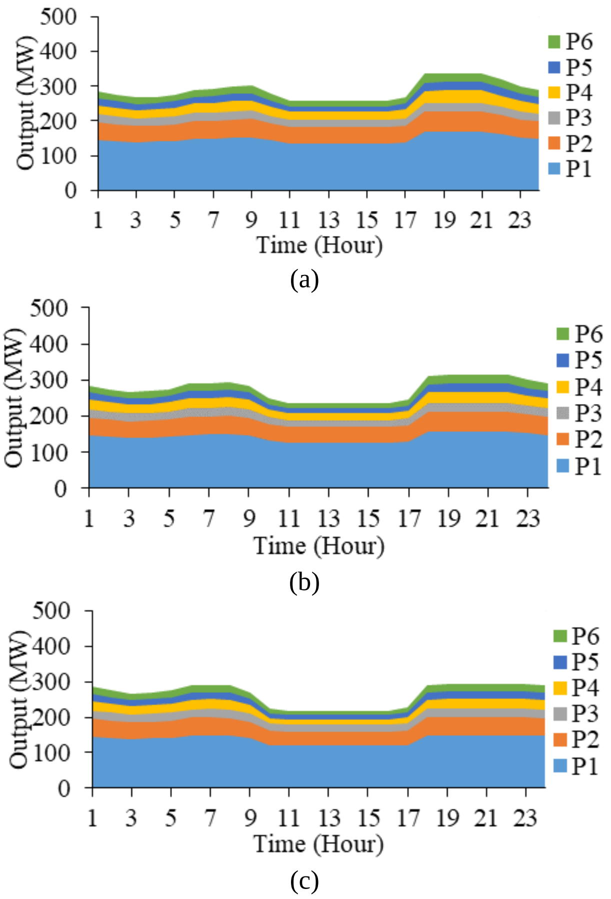

Figure. 8 Thermal generators output with CAES: (a) Case 1, (b) Case 2 and (c) Case 3

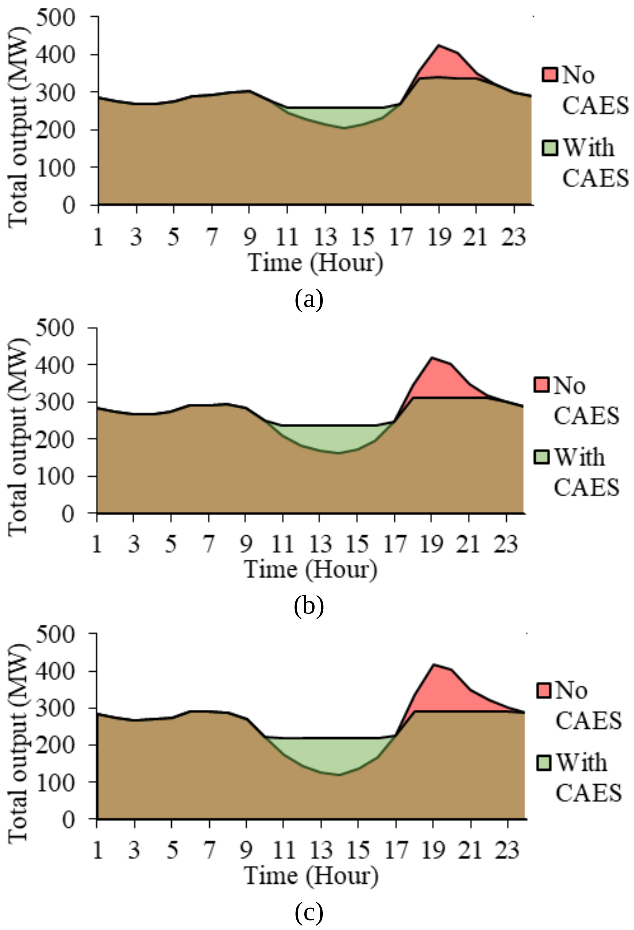

Figure. 9 Comparison of total thermal generators output power without and with CAES: (a) Case 1, (b) Case 2 and (c) Case 3

flexibility assessment based on Eqs. (13) to (17). Fig. 12 presents the system flexibility before considering CAES. As shown in the figure, a flexibility deficit occurs in the system. The upward flexibility deficit is 56 MW for case 1, 61 MW for case 2, and 66 MW for case 3. Fig. 13 shows the system flexibility after considering CAES. As can be seen, for each hour in the planning period, the flexibility of thermal generators and CAES is greater than the ramps of the load demand. No flexibility deficit occurs in the system, which means the proposed model effectively solves the duck curve fast ramps.

5.3 Performance comparison of the duck curve solution

The performance comparison of the proposed system against other methods for confronting the duck curve problem is shown in Table 6. The comparison includes the type of objective function, PV curtailment, load balancing management, economical approach, environmental approach, duck curve fast ramp, and operational flexibility. As can be seen, other methods in the literature have not integrated the environmental approach like

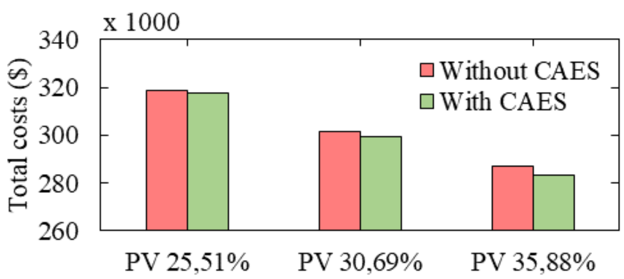

Figure. 10 Comparison of the total fuel costs of thermal generators

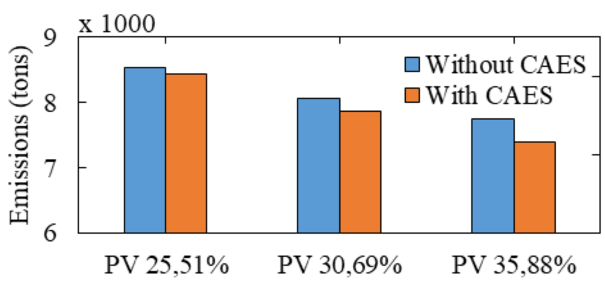

Figure. 11 Comparison of total thermal generators emissions

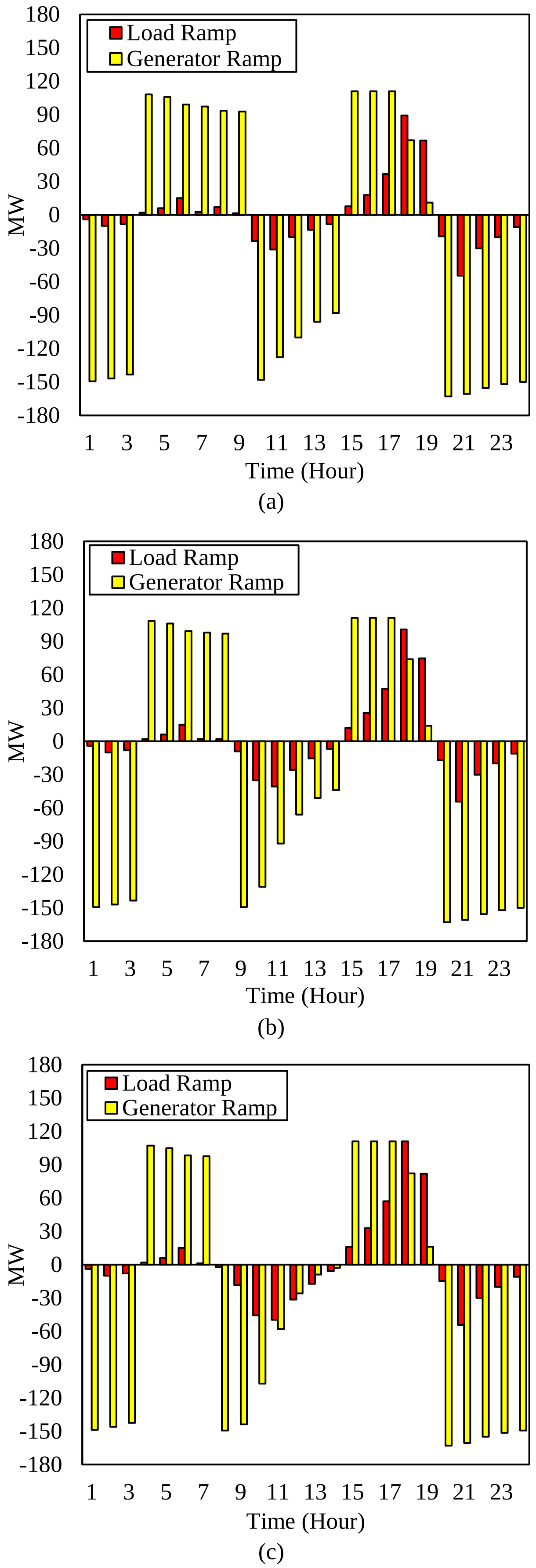

Figure. 12 System flexibility without CAES: (a) Case 1, (b) Case 2 and (c) Case 3

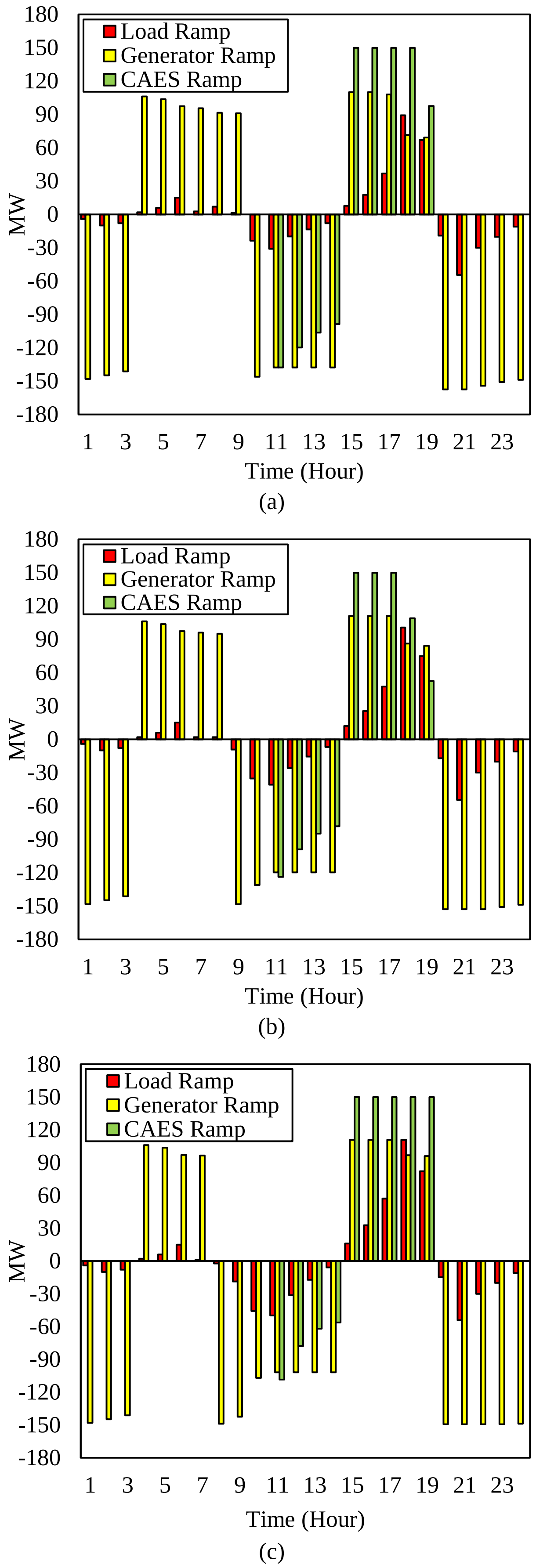

Figure. 13 System flexibility with CAES: (a) Case 1, (b) Case 2 and (c) Case 3

Table 6. Comparison of the duck curve solution performance

Performance	Type of objective function	PV Curtailment	Load balancing management	Economical approach	Environmental approach	DC fast ramp	Flexibility
Ref [5]	Single	Yes	Battery	Techno-economic analysis	No	No	No
Ref [6]	Single	Yes	Battery & demand response	No	No	Yes	No
Ref [8]	Single	No	Demand response	No	No	Yes	No
Ref [9]	Multi	No	Demand response	No	No	Yes	No
Ref [10]	Single	No	Demand response	Optimal dynamic pricing	No	No	No
Ref [11]	Single	No	Demand response	Optimal dynamic pricing	No	Yes	No
Ref [12]	Single	No	Flywheel	No	No	No	No
Ref [13]	Single	No	PSH	No	No	No	No
Ref [14]	Single	No	PSH	No	No	No	No
Ref [15]	Single	No	Battery	No	No	Yes	No
Ref [16]	Single	No	PSH & demand response	Unit commitment	Calculated	Yes	No
Ref [17]	Multi	No	Battery	Unit commitment	No	Yes	No
Ref [18]	Single	No	Battery	Economic dispatch	No	Yes	Yes
Proposed	Multi	No	CAES	Economic dispatch	Emission dispatch	Yes	Yes

emissions dispatch optimization into the existing system. In contrast, the proposed method considers the emission dispatch approach, which requires less additional cost and is easy to implement in the power system. This optimization is essential from the viewpoint of environmental protection because it can reduce the emissions of thermal generators. As a result, the combination of growth installations and penetration of PV as a clean energy source and reduced emissions by the thermal generator supports environmental sustainability.

Furthermore, the proposed method considers operational flexibility analysis to calculate the flexibility deficit, which determines the probability that the available power generation meets the load demand in a specific time scale without load shedding and curtailment. In the operational flexibility analysis, insufficient downward flexibility results in PV curtailment, while upward flexibility causes load shedding. This assessment is also essential in the duck curve situation. In the duck curve, there are critical periods when the load demand increases large and fast when the PV generation is zero at night at peak period and must be satisfied by the power system. So that the power system ramp must be greater than the load demand ramp, or the flexibility deficit must be zero.

6. Conclusions

The worldwide growth of PV installation has been inevitable in recent years as it has become the most competitive option for electrical energy generation. Consequently, demand for thermal generations decreases significantly during PV operation, which creates a duck curve. In this condition, the thermal generator efficiency becomes down and causes the fuel costs and emissions are increased.

This research develops a DEED model by determining CAES operation and dispatching the thermal generators' power output over twenty-four-hour periods to address the duck curve problem. This DEED model considers high PV penetration and CAES as energy storage, and its main target is to find the best-compromised solution for both the economic and environmental aspects.

This research uses three case studies in the IEEE 30-bus test system with six thermal generators, PV, and CAES power stations. The simulation results presented that the proposed DEED model successfully suppressed all cases in the duck curve and satisfied the direct objectives: reducing total fuel costs and emissions of thermal generators simultaneously. The total fuel cost was saved around $1180/day in case 1, $1970/day in case 2, and $3630/day in case 3, while the quantity of emissions was reduced by around 96.449 tons/day in case 1, 198.786 tons/day in case 2, and 351.193 tons/day for case 3.

In addition, according to the operational flexibility analysis, the proposed approach effectively handles the duck curve fast ramps, proved by no flexibility deficit in the planning periods.

Conflicts of interest

"The authors declare no conflict of interest."

Author contributions (Mandatory)

Conzeptualization, Patria Julianto, Adi Soeprijanto and Mardlijah; methodology, Patria Julianto, Adi Soeprijanto and Mardlijah; software, Patria Julianto; validation, Patria Julianto, Adi Soeprijanto and Mardlijah; formal analysis, Patria Julianto, Adi Soeprijanto and Mardlijah; investigation, Patria Julianto, Adi Soeprijanto and Mardlijah; resources, Patria Julianto; writing original data preparation, Patria Julianto, writing review and editing, Adi Soeprijanto and Mardlijah; visualization, Patria Julianto, Adi Soeprijanto and Mardlijah. "All authors have read and agreed to the published version of the manuscript."

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