Optimization models to flatten duck curve in power grid with high penetration of solar energy

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Received 23 Aug. 2023; Revised 31 Oct. 2023; Accepted 10 Nov. 2023; Published 25 Nov. 2023.
DOI: https://doi.org/10.54939/1859-1043.j.mst.91.2023.45-53

ABSTRACT

Currently, renewable energy sources are becoming increasingly popular worldwide as an alternative to reduce dependence on traditional energy sources, especially clean energy such as solar and wind energy. However, with a high level of solar energy integrated into the grid, operators are dealing with a new problem that can be visualized as the "duck curve", when the solar energy production is high and the demand are low. In this paper, optimal MIQP models with two different objective functions to overcome the duck curve is introduced. The models are evaluated in the California power grid (CAISO), where the penetration of solar energy is significant. The results show that the battery energy storage system can help to reduce the ramp rate of the duck curve up to 57.6%.

Keywords: Duck curve; BESS; Solar energy; CAISO; MIQP.

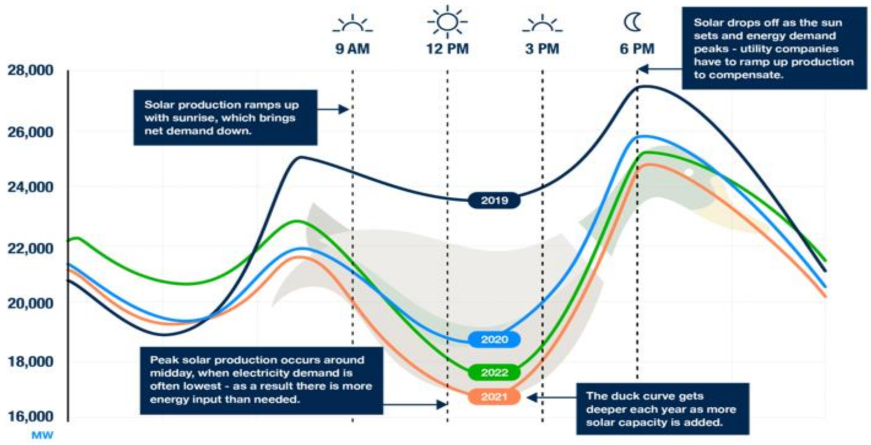
NOMENCLATURE

CAISO	California Independent System Operator	WT	Wind Turbines
MIQP	Mixed Integer Quadratic Program	RES	Renewable Energy Systems
BESS	Battery Energy Storage Systems	PSH	Pumped Hydro Storage
ESS	Energy Storage Systems	CSP	Concentrated Solar Power
PV	Photovoltaics	WOA	Whale Optimization Algorithm
P_t^{Load}	Load power at hour *t*	$P_{\max}^{\text{BATCh}}$	Maximum charging power of BESS
P_t^{BATCh}	Charging power of BESS during hour *t*	$P_{\max}^{\text{BATDis}}$	Maximum discharging power of BESS
P_t^{BATDis}	Discharging power of BESS during hour *t*	η	Charging/discharging efficiency of BESS
P_t^{PV}	Power generation of PV at time *t*	P_t^{PVcurt}	Power curtailment of PV at time *t*
P_t^{WT}	Power generation of WT at time *t*	$P_{t,\max}^{\text{PVf}}$	PV generation capacity during hour *t*
SOC_t^{BAT}	Capacity of BESS at time *t*	P_t^{WTcurt}	Power curtailment of WT at time *t*
$SOC_{\max}^{\text{BAT}}$	Maximum capacity of BESS	$P_{t,\max}^{\text{WTf}}$	WT generation capacity during hour *t*

DOD	Depth of Discharge of BESS	k_t^{PV}	PV penetration rate
u_t^{BAT}	Binary variable indicating the charging/discharging state of BESS	k_t^{WT}	WT penetration rate

1. INTRODUCTION

In recent years, renewable energy sources have experienced significant growth, attracting the attention of investors, grid operators and consumers. In addition to the benefits, one of the most concerning aspects is the impact of RES on the load profile. With increasing utilization, RES has directly impacted the daily load curve, posing challenges for grid operators due to the uncertainty. The excessive amount RES integrated into the power grid leads to a significant decline in the demand for conventional energy sources. This decline leads to the concept of "Netload" which refers to the actual load less all renewable generations. This phenomenon is very clear in regions with high solar energy, such as California. In March 2021, solar energy contributed nearly 40% of the state's electricity production for the first time. The significant penetration of RES has caused the daily load curve to gradually transition into the characteristic "Duck Curve" shape, as shown in figure 1. During the daytime, as the sun rises, the electricity demand starts to decrease due to the increase of solar energy generation. Subsequently, solar energy gradually increases and reaches its peak around midday when the electricity demand from the grid reaches its lowest point, forming the "belly" of the "duck." This decline is most pronounced on sunny days with cooler temperatures when people do not use electricity for cooling or heating, resulting in a deeper reduction in electricity demand. After midday and the evening, solar radiation gradually decreases. Meanwhile, the actual load demand gradually increases and reaches its peak. At this point, the neck and head of the "duck" are formed.



Solar drops off as the sun sets and energy demand peaks - utility companies have to ramp up production to compensate.

Solar production ramps up with sunrise, which brings net demand down.

Peak solar production occurs around midday, when electricity demand is often lowest - as a result there is more energy input than needed.

The duck curve gets deeper each year as more solar capacity is added.

Figure 1. *Image of Netload Curve [1].*

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The emergence of the "Duck Curve" on the power grid load curve has posed significant challenges for grid operators. First, the "Duck Curve" causes local electric grid overloading during peak solar energy hours. This phenomenon arises due to the transmission capacities of existing power grids and the development of power grids based on electricity planning not adequately accounting for the significant penetration of renewable energy sources, leading to an unavoidable situation of overload. Second, the increasing integration of solar energy has created difficulties in supply-demand balancing. This is due to the growing need for flexible dispatching of power plants to quickly generate electricity when the sun sets. During this time, the required capacity to be mobilized within a short period becomes immensely high. In addition, the frequency control systems are primarily located in conventional power plants such as hydro and thermal power plants. During the "belly of the duck" period, renewable energy becomes surplus and can meet electricity demand without relying on conventional energy sources. This poses the risk of shutting down these power plants. The shutdown of these plants affects grid stability and frequency.

Several studies have been proposed to solve the "Duck Curve" problem. An optimized schedule for the power grid in Taiwan by integrating RES with PHS, utilizing cost optimization functions and various constraints is introduced [2]. The results of this study demonstrate PHS can reduce the impacts of the "Duck Curve." Another approach is the use of ESS [3]. The results demonstrate that conventional power plants may face challenges in mobilizing resources during the "duck tail" period, which potentially necessitates the curtailment of renewable energy sources. This demonstrates the necessity of ESS, as they enable higher levels of RES penetration without the need for immediate mobilization. However, the research has not yet identified the specific utilization methods for ESS. The importance of ESS in balancing load during peak and off-peak hours has been emphasized in [4]. However, the article raises the issue of using CSP and PSH as energy sources for storage systems instead of high-cost BESS. A method for optimal sizing and control of the BESS to minimize losses within the system is presented in [5]. The "Duck Curve" is considered during the process of determining the location and size, optimized using the WOA, while the effectiveness of WOA is confirmed by Swarm Optimization Algorithms and Firefly Algorithm. The results show that WOA can determine the position and size of the BESS in all cases, thereby addressing the "Duck Curve". However, this comes with an economic trade-off, as the size of BESS is significantly increased compared to unconstrained scenarios.

Another method for smoothing ramp-rate and shifting power to the Netload is introduced [5]. The results show that the ramp-rate is reduced significantly, thereby partially addressing the challenge of flattening the "Duck Curve".

In this paper, we propose two optimization models to maximize the utilization of renewable energy sources while minimizing the negative impact of the "Duck Curve" on the system. Two distinct objective functions have been introduced for comparison. The California power grid was chosen as a case study for the research.

2. OPTIMIZATION MODELS

In this section, two different objective functions to flatten the Duck Curve are proposed. The first objective function is constructed to minimize the difference between Netload and Netloadlevel, which is a fixed value. This objective function is also known as Peak-Valley optimization.

$$\mathrm{F}_1 = \sum_{t=1}^{24}\left(P_t^{\mathrm{Load}} + P_t^{\mathrm{BATCh}} - P_t^{\mathrm{BATDis}} - P_t^{\mathrm{PV}} - P_t^{\mathrm{WT}} - Netloadlevel\right)^2 \rightarrow \min \tag{1}$$

$$Netloadlevel = \frac{\sum_{t=1}^{24}\left(P_t^{\mathrm{Load}} + P_t^{\mathrm{BATCh}} - P_t^{\mathrm{BATDis}} - P_t^{\mathrm{PV}} - P_t^{\mathrm{WT}}\right)}{24} \tag{2}$$

The second objective functions aim to reduce the ramp-rate of Netload, thereby minimizing the abrupt increase/decrease of a large amount of power from the grid in a short period. This objective function is formulated in equation (3).

$$\mathrm{F}_2 = \sum_{t=1}^{24}\left(Netload_t - Netload_{t-1}\right)^2 \rightarrow \min \tag{3}$$

BESS's Constraints

$$\left(1 - \mathrm{DOD}\right)\times SOC_{\max}^{\mathrm{BAT}} \le SOC_t^{\mathrm{BAT}} \le SOC_{\max}^{\mathrm{BAT}} \tag{4}$$

$$SOC_t^{\mathrm{BAT}} = SOC_{t-1}^{\mathrm{BAT}} + \eta\times P_t^{\mathrm{BATCh}} - \frac{P_t^{\mathrm{BATDis}}}{\eta} \tag{5}$$

$$0 \le P_t^{\mathrm{BATCh}} \le u_t^{\mathrm{BAT}} \times P_{\max}^{\mathrm{BATCh}} \tag{6}$$

$$0 \le P_t^{\mathrm{BATDis}} \le \left(1 - u_t^{\mathrm{BAT}}\right)\times P_{\max}^{\mathrm{BATDis}} \tag{7}$$

$$SOC_{t=0}^{\mathrm{BAT}} = SOC_{t=24}^{\mathrm{BAT}} \tag{8}$$

$$u_t^{\mathrm{BAT}} \in \left\{0; 1\right\} \tag{9}$$

Constraint (4) ensures that the energy stored in BESS remains within a certain range. Constraint (5) presents the total energy of BESS at time t. Depending on the charging/discharging power, this value will vary at different time points. Constraints (6) and (7) require that the charging/discharging power of BESS always stays within the allowable values. Additionally, constraint (8) demands that the energy stored in BESS after each day needs to be restored to an initial value. Finally, the binary variable u_t^{BAT} in constraint (9) represents the charging/discharging state of BESS at each time point.

RES's Constraints

$$P_{t,\min}^{\mathrm{PV}} \le P_t^{\mathrm{PVout}} + P_t^{\mathrm{PVcurt}} \le P_t^{\mathrm{PVft}} \tag{10}$$

$$P_{t,\min}^{\mathrm{WT}} \le P_t^{\mathrm{WTout}} + P_t^{\mathrm{WTcurt}} \le P_t^{\mathrm{WTf}} \tag{11}$$

$$P_t^{\mathrm{PVout}} \ge k_t^{\mathrm{PV}} \times P_t^{\mathrm{PVf}} \tag{12}$$

$$P_t^{\mathrm{WTout}} \ge k_t^{\mathrm{WT}} \times P_t^{\mathrm{WTf}} \tag{13}$$

$$P_t^{\mathrm{PVout}} \,\&\, P_t^{\mathrm{PVcurt}} \ge 0 \tag{14}$$

$$P_t^{\text{WTout}} \,\&\, P_t^{\text{WTcurt}} \geq 0 \tag{15}$$

$$k_t^{\text{PV}} \,\&\, k_t^{\text{WT}} \in [0;1] \tag{16}$$

In constraints (10) and (11), the total power injection into the system and the power curtailment of RES during the RES hour must always be greater than the minimum generation power specified by the technical characteristics of RES, while not exceeding the forecasted values. Constraints (12) and (13) characterize the penetration of RES into the system. Constraints (14) and (15) express that the injection and curtailment power is always non-negative. Lastly, constraint (16) requires the variables representing the RES penetration to fall within [0, 1].

3. CALIFORNIA POWER GRID

California is one of the largest economies in the world and leads the United States in the production of electricity from renewable energy sources such as solar energy, wind energy, and geothermal energy. According to statistics in 2021, natural gas is the primary source of electricity generation, accounting for nearly half of the state's total capacity. It is followed by solar energy (17.4%) and wind energy (7.9%) in terms of their share of the energy mix. Figure 2 illustrates that the total installed capacity of solar energy and wind energy accounts for approximately 28.6%. Therefore, California is actively promoting the development of renewable energy sources and actively pursuing energy transition goals.

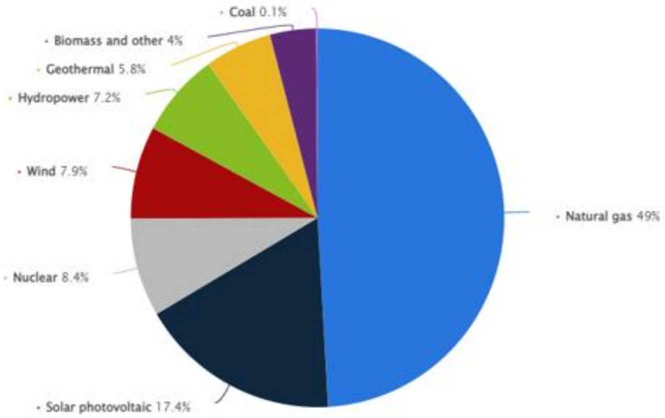

Figure 2. *Image of the power generation structure of California in 2021.*

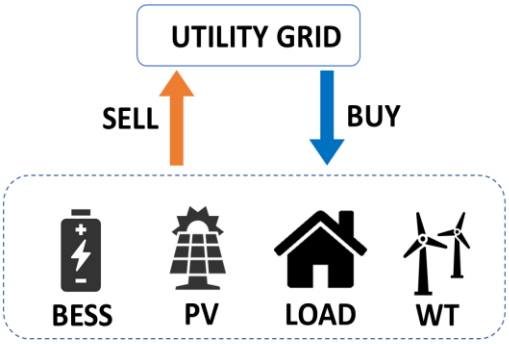

Figure 3. *Image of California's power grid model.*

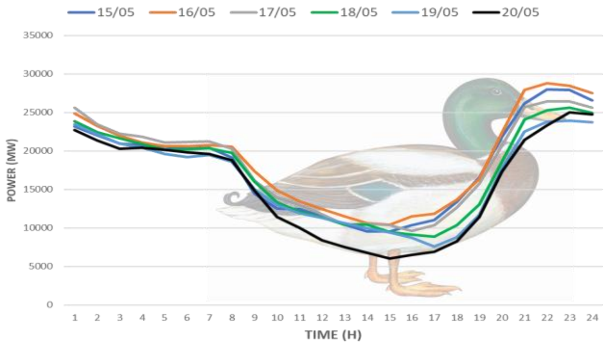

Figure 4. *Image of Netload data in California from May 15th to May 20th 2023.*

According to the EIA, the state had already achieved its target of 33% retail electricity sales from eligible renewable energy sources by 2020, three years ahead of schedule. The vision for 2030 is to reach 60% of retail sales from renewable energy, and by 2045, the target is set at 100%. For convenience in calculations, except for RES and BESS, conventional power sources will be considered as grid sources. The California grid, after simplification, has a structure as shown in figure 3.

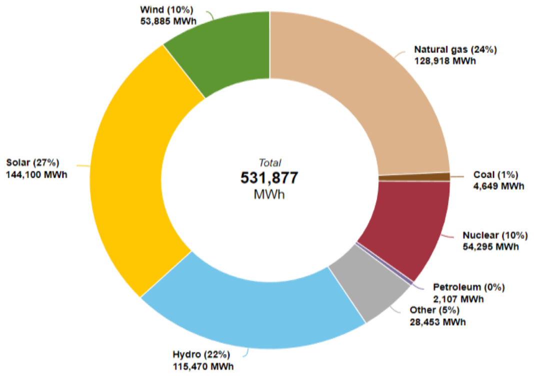

Figure 5. *Image of Power generation in California May 20th 2023.*

4. RESULTS

In this section, we apply the MIQP model presented in Section 2 to validate the Duck Curve flattening effect in the simplified California power grid model shown in Section 3. GAMS software with CPLEX solver is used to solve the MIQP. In this study, the forecast error is neglected. The data regarding the Netload curve for six days in May 2023 were collected from CAISO (figure 4). In order to assess the impacts of the proposed optimization model on flattening the Duck Curve, the day with the lowest duck belly within the six-day period (May 20th) is selected as the input data. Figure 5 illustrates the power generation from the integration of various power generations of the California power grid. Figure 6 provides detailed information on the power profiles of the load and RES over a 24-hour period.

In general, the operational plans implemented through running the optimization model in both scenarios can successfully transform the "Duck Curve" into a "Flatybus Curve".

Figure 7 demonstrates that the steepest ramp-rate of the Netload curve occurs between 18:00 and 21:00. Within just a three-hour window, the required power capacity to meet the load demand reaches 13.2 GW (table 1). The optimized results show an improved Netload curve (represented by the purple and orange curves) throughout the entire study period. Compared to the Netload curve without the involvement of BESS, Peak-Valley model helps reduce the slope by up to 36.4% (ΔP_1=8.4GW). This figure goes up to 57.6% (ΔP_2=5.6GW) in Ramp-rate model during the same period (18:00-21:00). Moreover, both models contribute to bringing down the peak load (at 23:00) from 24.9 GW to 21.9 GW.

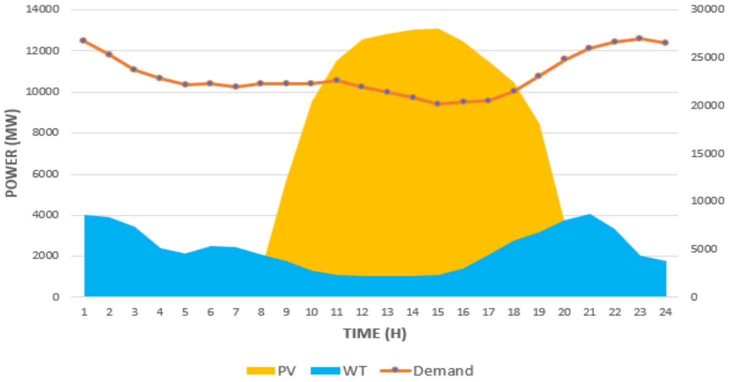

Figure 6. *Image of load and RES on 20/05/2023.*

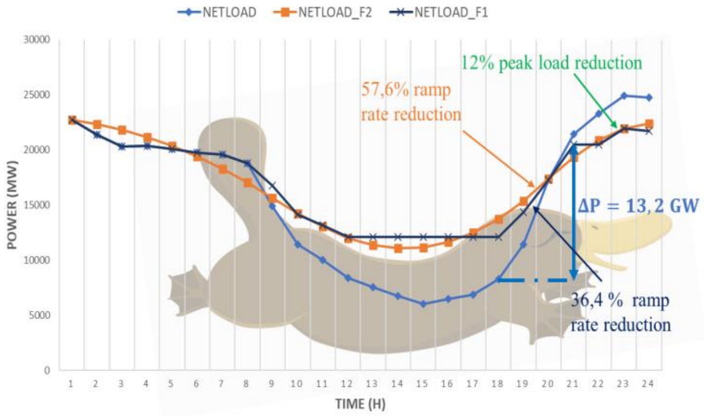

Figure 7. *Image of comparison between two models.*

Table 1. *Comparison between two models.*

	Peak-Valley model	**Ramp-Rate reduction model**
Ramp rate reduction from 18 pm to 21 pm (MW)	8396,86	5620,15
PV Curtailment (MW)	30311,5	29316,3
WT Curtailment (MW)	4466,8	4451
RES Curtailment (%)	19	18,5

The operational parameters of ESS are presented in figure 8 and figure 9. From these results, it can be observed that the ramp-rate model has contributed to increasing the penetration rate of RES, thereby minimizing the operational costs of the system. Table 1 demonstrates that the RES curtailment of both models are roughly the same.

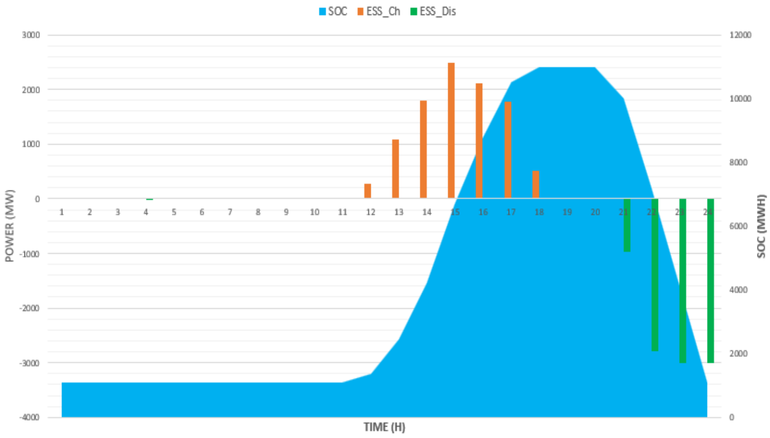

Figure 8. *Image of operating parameters of ESS by Peak-Valley model.*

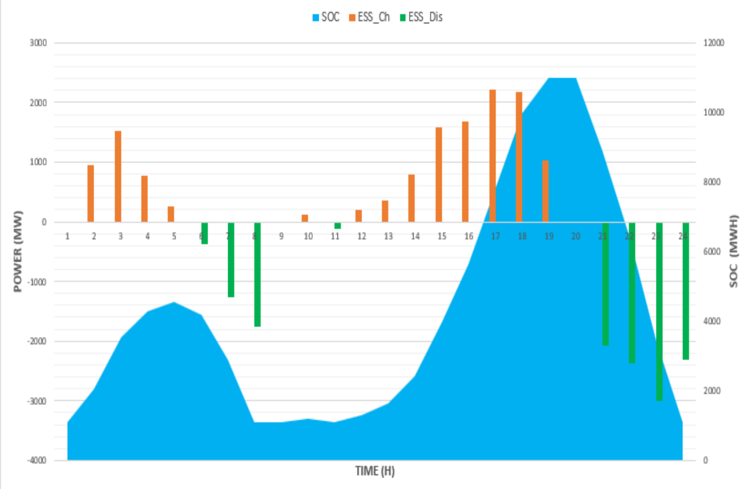

Figure 9. *Image of operating parameters of ESS by rate reduction model.*

5. CONCLUSIONS

In this study, optimization models based on MIQP to flatten the Duck Curve are presented. The proposed models are examined in California power grid. The models effectively address two issues simultaneously: flattening the Netload curve and increasing the penetration rate of RES into the system. In further work, additional nonlinear constraints related to the stochastic of renewable energy sources will be studied. Factors such as load forecasting errors and RES will also be taken into consideration.

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TÓM TẮT

Nghiên cứu mô hình tối ưu làm phẳng "Duck curve" của lưới điện có tỉ lệ xâm nhập cao của điện mặt trời

Hiện nay, các nguồn năng lượng tái tạo đang ngày càng trở nên phổ biến trên toàn thế giới như một giải pháp thay thế nhằm giảm bớt sự phụ thuộc vào các nguồn năng lượng truyền thống, đặc biệt là năng lượng sạch như năng lượng mặt trời và năng lượng gió. Tuy nhiên, với mức độ cao của năng lượng mặt trời được tích hợp vào lưới điện, các nhà khai thác đang phải đối phó với một vấn đề mới có thể được hình dung là "Duck Curve", khi lượng điện cung cấp từ năng lượng mặt trời cao và nhu cầu sử dụng thấp. Trong bài báo này, mô hình tối ưu MIQP với hai hàm mục tiêu khác nhau nhằm san phẳng đường cong vịt được đề xuất. Các mô hình được đánh giá trong lưới điện California (CAISO), nơi mà sự thâm nhập của năng lượng mặt trời là đáng kể. Kết quả cho thấy, hệ thống lưu trữ năng lượng bằng pin có thể giúp giảm độ dốc của Duck Curve lên tới 57,6%.

Từ khoá: Đường cong vịt; Hệ thống lưu trữ; Năng lượng mặt trời; CAISO; MIQP.