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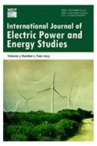

Research on Capacity Configuration of Drilling Microgrid based on Gas-Energy Storage System

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ABSTRACT

To address the industry challenges of mismatched power output from gas generators and dynamic downhole load demand in drilling operations, along with the lack of scientific configuration basis for the coordinated operation of energy storage systems and traditional power generation equipment, this study conducts an in-depth optimization study on a hybrid gas-energy storage power supply system using a 50DB drilling rig as the specific research object. Historical load power data of the rig during typical operating cycles were systematically collected and analyzed. Based on this, a cost optimization model for the coordinated gas-energy storage power supply was developed, aiming to minimize the total life-cycle cost. This model innovatively integrates key economic factors, including the initial investment and long-term operation and maintenance costs of the battery energy storage system, as well as the fuel consumption and maintenance costs of the gas generator sets. The optimization objectives are the lowest overall system cost and the optimal energy storage capacity configuration. The results indicate that: ① While meeting the actual power demand, the optimal capacity of the energy storage battery is 1870 kWh, and the optimal charging/discharging power is 992 kW; ② The number of gas generator sets on site can be optimized from the original 8 to 4. This allows the units to operate stably within their high-efficiency range, increasing the average operating efficiency significantly from a maximum of 22.7% before optimization to 42.6%; ③ Under extreme working conditions with the maximum load during drilling operations, the optimally configured energy storage system can independently support the full site load for 4 hours, greatly enhancing the reliability and resilience of the power supply system.

KEYWORDS

Gas-fired Power Generation; Energy Storage Systems; Oil Drilling; Islanded Operation; Optimal Configuration.

1. INTRODUCTION

Driven by increasingly stringent environmental regulations and the continuous growth in energy demand, traditional power generation systems are undergoing profound transformation and upgrading. At present, key research directions in the energy sector focus on the development of advanced energy conversion technologies aimed at improving energy utilization efficiency while mitigating environmental impacts. At the same time, it is essential to ensure that energy conversion processes do not induce adverse environmental effects such as global warming or pollutant emissions [1,2,3].

Existing power supply modes for drilling platforms can be classified into four categories: standalone diesel generator supply, grid-connected diesel generator supply, grid-connected gas generator supply, and standalone gas generator supply. Among these, the standalone diesel generator mode is characterized by high carbon emissions and has been gradually phased out. Currently, the grid + diesel generator and grid + gas generator modes are predominantly adopted, where generators mainly serve as backup power sources in the event of grid failures. When the cost of grid construction exceeds that of standalone gas generator deployment, an independent gas generator power supply mode is employed, providing continuous and low-carbon electricity for remote drilling crews.

Owing to their high efficiency, operational flexibility, and relatively low carbon emissions, gas generator systems play a critical role in modern energy structures [4,5]. However, during drilling operations, gas generators still face challenges in effectively responding to impact loads and power fluctuations. This limitation is primarily attributed to their relatively slow dynamic response, which necessitates excessive power capacity allocation to ensure supply reliability, thereby leading to energy waste and potential system instability [6,7]. Consequently, improving the operational strategy of gas generator systems and reducing energy losses caused by load fluctuations has become an urgent research issue.

Supercapacitors and batteries, with advantages such as long service life, high charge–discharge efficiency, and rapid response capability, can effectively address large load fluctuations in drilling equipment [8, 9]. These energy storage technologies compensate for the mismatch between generation output and load demand caused by the delayed response of gas generators [10]. Wang Shuai et al. [11] investigated the application of supercapacitor energy storage units in micro gas turbine power generation systems to compensate for insufficient instantaneous power output under impact loads, thereby achieving fast compensation control. Sun Hongbin et al. [12] introduced a super energy storage system into drilling platforms, significantly enhancing the single-unit load-carrying capacity and impact load resistance of gas generators. Their compensation system was capable of replacing two 300 kW gas generators, reducing the initial investment in generator capacity. Thompson and Richard et al. [13], based on 46 days of drilling rig operational data, proposed a modular lithium battery energy storage system combined with a DC/DC control architecture. Through empirical analysis, they demonstrated reductions in gas consumption and improvements in generation efficiency, while also providing a practical engineering solution. Although these studies have confirmed the effectiveness of hybrid power supply systems integrating gas generators with energy storage, battery selection-an essential aspect of system design-has not been supported by a systematic and scientific sizing methodology.

Given the persistently high cost of batteries, the integration of energy storage systems substantially increases the overall investment burden of gas-fired power stations. At present, battery capacity selection is largely based on empirical approaches, lacking systematic rigor and accuracy. This often results in improper capacity sizing or redundant configuration, leading to reduced operational efficiency, poor life-cycle economic performance, and difficulties in balancing system performance and cost [13, 14].

To address these limitations, this paper proposes a cost optimization model for a gas–energy storage coordinated power supply system. The model incorporates key economic factors, including the initial investment cost of the energy storage system, operation and maintenance costs, and the operational costs of gas generators. Based on actual operational data, the model determines the optimal battery capacity configuration for a given drilling crew. With the objectives of minimizing total power generation system cost and optimizing capacity allocation, the coordinated operating mechanism between gas generators and energy storage systems is comprehensively analyzed. Using real load power data from a 50DB drilling platform, the joint operation of gas generators and energy storage is optimized to enhance the energy efficiency and economic performance of the drilling power supply system. The proposed model not only reduces the energy consumption of gas generators but also enables optimal capacity allocation of energy storage within gas-based distribution networks. The main innovation lies in dynamically adjusting the number of operating gas generators and the output power of the energy storage system, thereby significantly improving overall system efficiency and operational stability. This work provides an economically viable, efficient, and reliable power supply solution for drilling operations.

2. FIELD MICROGRID STRUCTURE AND DATA ANALYSIS

The existing structure of the 50DB drilling microgrid is illustrated in Fig. 1. Gas generators supply power directly to the load equipment through corresponding power conversion units. The load subsystem consists of high-power drilling equipment and low-voltage auxiliary devices, which are connected to a common DC bus via appropriate power electronic converters.

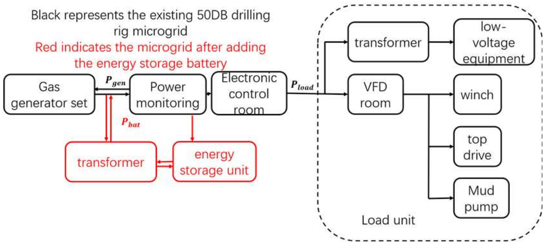

Fig. 1 Schematic diagram of microgrid structure

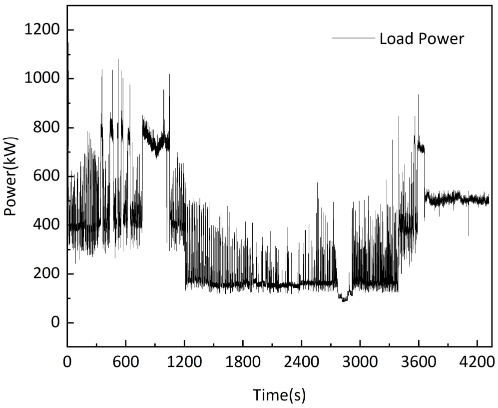

Fig. 2 Load data of the well team for one day

Fig. 2 depicts the daily power consumption profile of the drilling crew during drilling operations. The drilling process includes four key operating conditions: tripping out, tripping in, drilling, and coring. These operating conditions exhibit significantly higher power consumption than other modes and represent the most frequently occurring stages in a complete drilling cycle. Moreover, their power ramp rates are notably high, resulting in pronounced power fluctuations. During tripping operations, frequent hoisting and lowering of the drill string by the drawworks lead to short-duration power peaks with large fluctuations but relatively low total energy consumption. During normal drilling, the mud pumps and top drive operate simultaneously, and the load power is generally maintained at a high level. However, in practical operations, uncertainties such as directional drilling adjustments, abnormal mud pump pressure, or complex geological conditions often require temporary pump shutdowns or equipment switching, causing abrupt changes in power demand. Once the coring stage begins, the power profile becomes more stable. In this phase, the drawworks provides a constant weight on bit, the top drive performs precise drilling operations, and the mud pump operates at low speed. The coordinated operation of these units effectively suppresses power fluctuations, resulting in a relatively stable overall power demand.

Fig. 3 shows that the electrical load of the drilling rig is characterized by a large proportion of time spent in low-power operating states. Although the power demand remains within 0–200 kW and around 600 kW for most of the operating period, with high-power conditions occurring infrequently and contributing little to total energy consumption, gas generators are unable to rapidly track such power variations due to their limited dynamic response. Consequently, generators are typically operated at power levels higher than the maximum demand of these operating conditions [15]. This operating strategy leads to a low single-unit load factor, generally below 40%, resulting in increased gas consumption and poor economic performance [14]. As shown in Fig. 4, when the load factor falls below 40%, generator efficiency drops sharply. The integration of an energy storage system can effectively address this issue. (Loading rate = Current gas generator's power generation capacity / generator rated power ×100%)

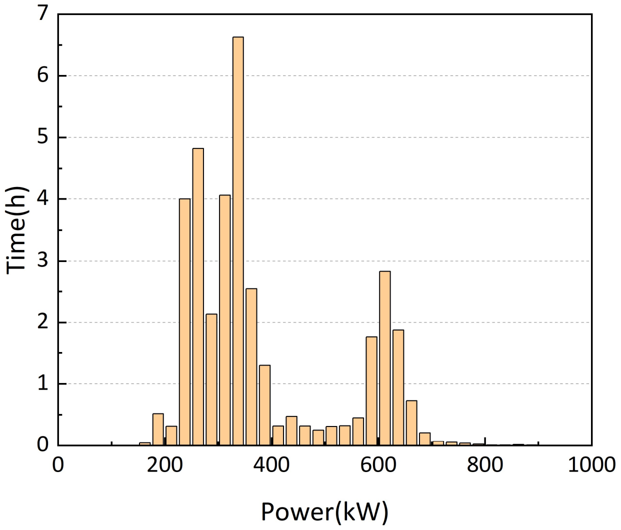

Fig. 3 Histogram of drilling rig load distribution

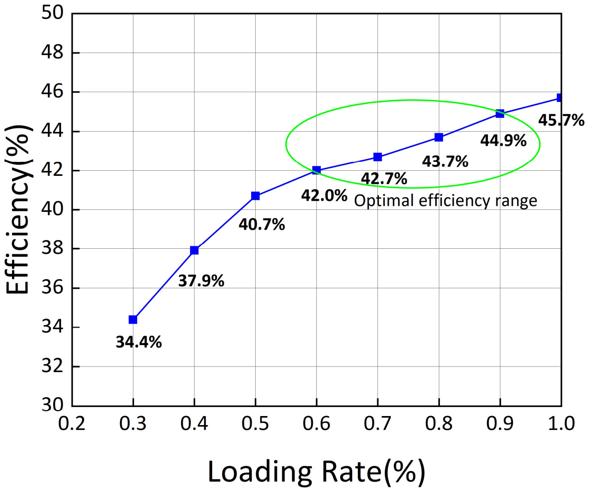

Fig. 4 Gas generator Efficiency Diagram

3. SELECTION OF BATTERY ENERGY STORAGE SYSTEMS

The core of energy storage system design lies in determining the battery chemistry as well as key parameters such as rated power and capacity. Even when batteries have identical capacity ratings, significant differences in total cost may arise due to the use of different materials.

3.1. Energy Storage Battery Materials

A variety of battery technologies can be adopted in energy storage systems, each offering distinct technical advantages. In practical selection, both technical performance and economic feasibility must be comprehensively evaluated to achieve an optimal cost–performance balance. Taking lithium iron phosphate (LFP) batteries, lithium titanate (LTO) batteries, and supercapacitors(SCT) as examples, Fig. 5 compares the costs of energy storage batteries based on different materials, while the corresponding technical parameters are listed in Table 1. Among these options, LFP batteries stand out due to their mature commercialization, technological reliability, and relatively low cost, demonstrating superior cost-effectiveness. Therefore, LFP batteries are selected in this study.

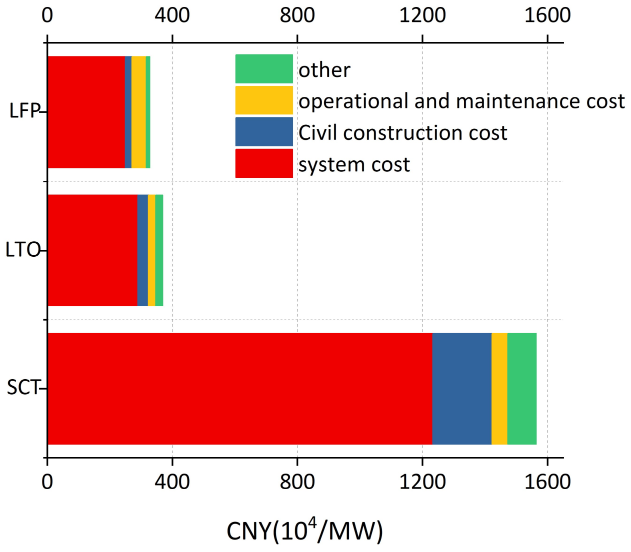

Fig. 5 Costs of energy storage batteries made of different materials

Table 1. Comparison of Energy Storage Technologies

Item	LFP Battery	LTO Battery	Supercapacitor
Energy density (Wh/kg)	80～170	60～100	2.5～15
Power density (W/kg)	1500～2500	> 3000	1000～10000
Cycle life	2000～10000	> 10000	$>10^6$
Investment cost (CNY/kWh)	800～1600	4500	9500～13500

3.2. Operational Settings of the Energy Storage System

The capacity configuration of the energy storage system directly affects the duration of continuous power supply. Although a larger capacity can extend operating time, the associated additional investment may far exceed the savings in gas fuel costs, thereby increasing the overall system cost. Conversely, insufficient capacity may fail to meet load demand, requiring frequent start-up and shutdown of gas generators to compensate for power shortages. This not only increases fuel consumption but also undermines the objective of reducing generator cycling.

To address this trade-off, an optimization model for coordinated operation between gas generators and the energy storage system is developed. This model facilitates efficiency improvement and rational configuration of battery capacity and power ratings. The primary objective is to maintain the operating load factor of gas generators within the high-efficiency and stable range of 60%–90%. The corresponding operational strategies are defined as follows.

Base operating mode: One or more gas generators operate at a 60% load factor, while the battery dynamically compensates for power imbalances. When the load demand falls below 40% of the rated power of a single generator, one generator is shut down to improve operational efficiency. When the load demand exceeds 90%, an additional generator is brought online to ensure system stability.

Battery charging mode: When the battery state of charge (SOC) drops below 20%, the system automatically switches to charging mode. Battery discharge is suspended, one additional gas generator is started, and all online generators operate at a 90% load factor to simultaneously meet load demand and charge the battery. Once the battery SOC recovers to above 80%, the system returns to the base operating mode: one generator is shut down, generator load factors are restored to 60%, and the battery resumes participation in power regulation.

Based on the original microgrid architecture, an energy storage battery system is integrated, resulting in the modified microgrid configuration shown in Fig. 1. Gas generators and batteries are connected to the DC bus through appropriate power conversion interfaces. The energy storage unit, implemented as a battery bank, absorbs surplus bus power or compensates for power deficits, thereby reducing fluctuations in gas generator output. Neglecting line and switching losses, the power balance on the DC bus under islanded operation is expressed as:

$$\Delta P(t) = P_{gen}(t) - P_{load}(t) = P_{bat}(t) \tag{1}$$

Where $\Delta P(t)$ represents the variation in total DC bus power under islanded conditions; $P_{load}(t)$ is the load power demand; $P_{gen}(t)$denotes the total power output of the gas generators; and $P_{bat}(t)$ is the battery power.

The 50DB drilling crew is supplied by eight gas generators, each with a rated power of 350 kW. With the integration of the energy storage system, as illustrated in Fig. 6, the load power $P_{load}(t)$ in the microgrid typically exhibits pronounced fluctuations. The energy storage battery supplements power when the drilling equipment demand exceeds the total generator output. Specifically, the battery discharges when load power exceeds generator output and charges when excess power is available. In this manner, stable operation of drilling equipment is ensured without additional generator start–stop actions, thereby improving overall economic performance and system reliability.

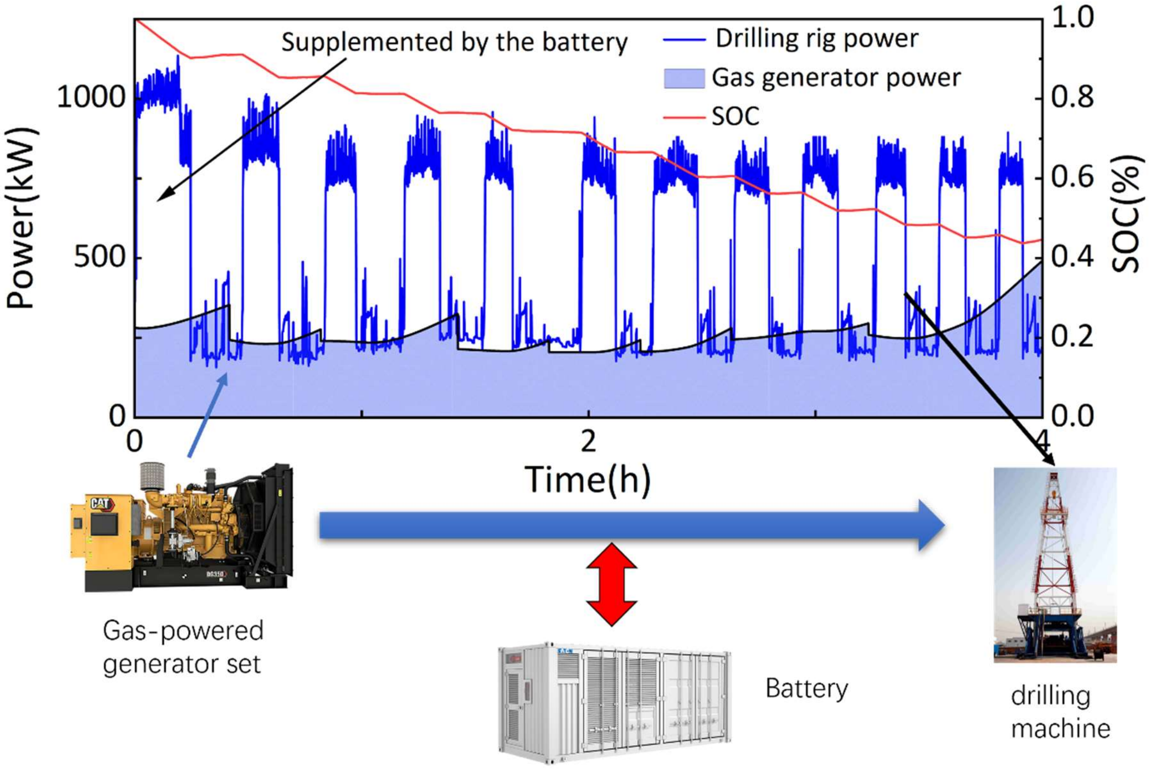

Fig. 6 Schematic diagram of the gas generator + energy storage system supplying the drilling crew

3.3. Calculation of Battery Rated Power and Rated Capacity

The rated power of the energy storage system should be sufficient to smooth power imbalances between generation and load. Considering charging and discharging efficiencies, the rated battery power is defined as:

$$P_{BN} = max\{P_{Charge}, P_{Discharge}\} \tag{2}$$

$$P_{Charge} = |min\ p_{bat}(t)|\eta_{bat,c} \tag{3}$$

$$P_{Discharge} = |max\ p_{bat}(t)|/\eta_{bat,d} \tag{4}$$

Where P_{Charge} and $P_{Discharge}$ denote the charging and discharging power of the battery, respectively; $\eta_{bat,c}$ and $\eta_{bat,b}$ are the charging and discharging efficiencies.

The battery SOC at time t is expressed as:

$$SOC_{Bat}(t) = SOC_{Bat0} - \sum_{t=1}^{n} \frac{P_b(\mathrm{t})\Delta \mathrm{t}}{E_{BN}} \tag{5}$$

Where SOC_{Bat0} is the initial SOC, $\Delta\mathrm{t}$ is the control time step, E_{BN} is the rated battery capacity, and $P_b(\mathrm{t})$ is the battery power reference value accounting for charging and discharging efficiencies, defined as:

$$P_b(\mathrm{t}) = \begin{cases} p_{bat}(t)\eta_{bat,c} & p_{bat}(t) < 0 \\ \frac{p_{bat}(t)}{\eta_{bat,d}} & p_{bat}(t) \geq 0 \end{cases} \tag{6}$$

Considering SOC constraints, the following condition must be satisfied:

$$\begin{cases} \min[SOC_{Bat}(t)] \geq SOC_{min} \\ \max[SOC_{Bat}(t)] \leq SOC_{max} \end{cases} \tag{7}$$

Finally, the natural gas consumption cost of the gas generators is closely related to their operating efficiency. Fuel consumption depends on the electrical power output and the instantaneous efficiency, which can be expressed as:

$$m_f = \frac{P_{gen}}{\eta(LR) \cdot LHV} \tag{8}$$

Where $\eta(LR)$ denotes the electrical efficiency at the current load ratio, and LHV is the lower heating value of the fuel.

4. OPTIMAL CONFIGURATION MODEL OF THE GAS GENERATOR–BATTERY ENERGY STORAGE SYSTEM

Considering the initial investment cost, operation and maintenance cost, and replacement cost, an optimal configuration model for the battery energy storage system is established with the annualized comprehensive battery cost as the objective function. To achieve minimization of the overall cost, the battery capacity is treated as the decision variable. By simulating system costs under different battery capacity configurations, the required maximum charging and discharging power can be determined, and the configuration that yields the minimum total cost is ultimately identified. The flowchart of the proposed optimization model is shown in Fig. 7.

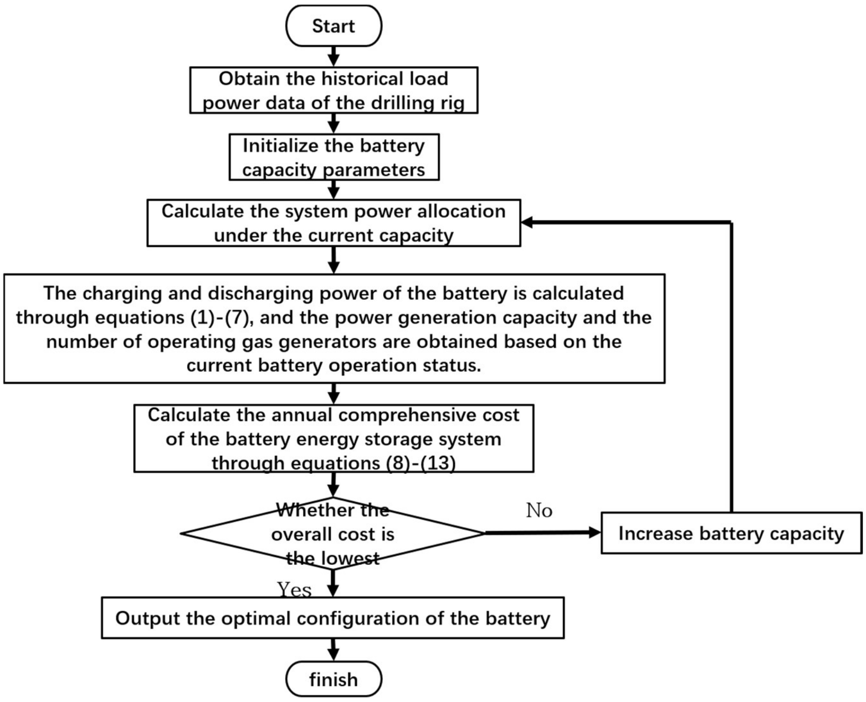

Fig. 7 Optimal configuration process of the battery energy system

4.1. Objective Function

The annual comprehensive cost of the energy storage system is defined as:

$$C_{tol} = C_{inv} + C_{main} + C_{gen} \tag{9}$$

Where C_{inv} denotes the initial investment cost of the battery energy storage system; C_{main} represents the operation and maintenance cost of the storage system; and C_{gen} is the operation and maintenance cost of the gas generators.

The initial investment cost of the energy storage system is expressed as:

$$C_{inv} = (c_{Pbat}P_{BN} + c_{Ebat}E_{BN})\gamma + C_{bop}E_{BN} \tag{10}$$

Where P_{BN} and c_{Ebat} denote the unit investment costs of battery power and battery capacity, respectively; C_{bop} is the balance-of-plant (BOP) and civil construction cost per kilowatt-hour; and γ is the capital recovery factor, defined as:

$$\gamma = \frac{r(1+r)^{T_N}}{(1+r)^{T_N-1}} \tag{11}$$

Where r is the discount rate and T_N is the rated service life of the battery energy storage system.

The operation and maintenance cost of the energy storage system is given by:

$$C_{main} = C_{rep}E_{BN} \tag{12}$$

where C_{rep} is the operation and maintenance cost per kilowatt-hour of the storage system, including depreciation, labor costs, and partial replacement costs of storage components required to ensure normal operation.

The operation and maintenance cost of the gas generators C_{gen} is expressed as:

$$C_{gen} = m_f c_{fuel} + m_{gen} N_{max} \tag{13}$$

Where m_f is the amount of natural gas consumed by the generators, c_{fuel} is the fuel cost per kilogram, m_{gen} is the maintenance cost per gas generator, and N_{max} is the maximum number of operating gas generators.

4.2. Constraints

During discharging operation of the gas generator–energy storage system, the following constraint must be satisfied:

$$P_{gen} + P_{Discharge} \geq P_{load}(t) \tag{14}$$

During charging operation, the system is subject to:

$$P_{gen} - P_{charge} \geq P_{load}(t) \tag{15}$$

5. CASE STUDY

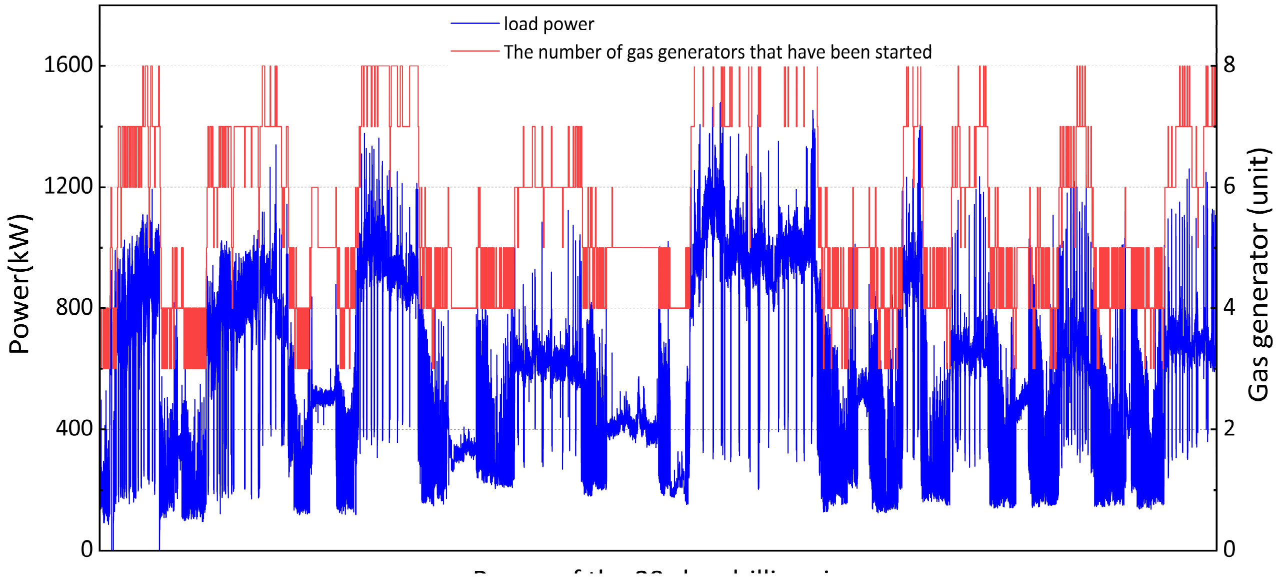

Fig. 8 Number of online generator sets and drilling rig load curve over 29 days

To verify the feasibility and cost-effectiveness of the proposed model, a case study was conducted using 29 days of load data from a 50DB drilling crew, with a sampling interval of 3 s. As shown in Fig. 8, the blue curve represents the power demand profile required to complete one well, while the red curve indicates the number of online gas generator sets in the absence of an energy storage system.

Based on the preceding analysis, lithium iron phosphate (LFP) batteries were selected as the energy storage medium. Using Eqs. (2)–(15) and the parameters listed in Table 2, simulations were performed to determine the optimal configuration. The resulting optimal values are summarized in Table 3.

Table 2. Relevant Parameters of Battery Energy Storage System

Equipment	Parameter	Value
Battery	SOC_{bat}^{origin}	0.5
	SOC_{bat}^{min}	0.2
	SOC_{bat}^{max}	0.8
	η_{bat}	0.95
	$c_{Pbat}(¥/kW)$	5000
	$c_{Ebat}(¥/kWh)$	1500
	$T_N(year)$	5
	γ	0.06
	$C_{rep}(¥/kWh)$	240
	$C_{bop}(¥/kWh)$	280
Gas generator	$max_{capacity}(kW)$	350
	$min_{capacity}(kW)$	0
	$m_{gen}(¥/year)$	70000
	$c_{fuel}(¥/kg)$	0.0385
	LHV	13888.9

Table 3. Overall Optimal Value

Equipment	Optimal battery capacity /kWh	Optimal charge/discharge power /kW
Battery	1870	992

The optimal battery capacity is determined to be 1870 kWh, with a corresponding charge/discharge power of 992 kW. In practical engineering applications, standardized battery capacities of 1000 kWh and 2000 kWh are commonly adopted. The full life-cycle costs associated with different battery capacities are compared in Table 4. Compared with the empirically selected capacities of 1000 kWh and 2000 kWh, the optimized 1870 kWh configuration reduces the total life-cycle cost by 15.3% and 13.7%, respectively.

Table 4. Comparison of full-cycle Costs under Different capacities

Battery capacity /kwh	Full life-cycle cost /10^4 CNY
1000	650
1870	637
2000	550

With an energy storage battery configured at 1870 kWh and a charge/discharge power of 922 kW, the number of operating gas generators and unnecessary generator start–stop events can be significantly reduced, while the generation efficiency of the gas generators is markedly improved. As shown in Figs. 9 and 10, in the absence of an energy storage system, up to eight gas generators are required, with an average efficiency of approximately 20% per unit, and frequent switching between three and four operating generators. In contrast, when the 1870 kWh / 922 kW energy storage system is deployed, the maximum number of operating gas generators is reduced from eight to four, and the switching frequency is substantially lowered. Meanwhile, generator efficiency increases from approximately 20% to a maximum of 42.6%.

When all gas generators are shut down, the energy storage system alone can sustain full-load drilling operations (two-open drilling condition) for up to 4 hours. As illustrated in Fig. 11, under islanded operation supplied entirely by the energy storage system, the SOC decreases from full charge to zero over a continuous supply duration of approximately 4 hours for the configuration of 1870 kWh capacity and 992 kW charge/discharge power. This backup power capability provides sufficient response time for on-site operation and maintenance personnel, ensuring continuity of power supply during generator maintenance and effectively preventing drilling interruptions caused by power outages.

The above results demonstrate that a battery capacity of 1870 kWh achieves an optimal balance between system reliability, economic performance, and operational efficiency.

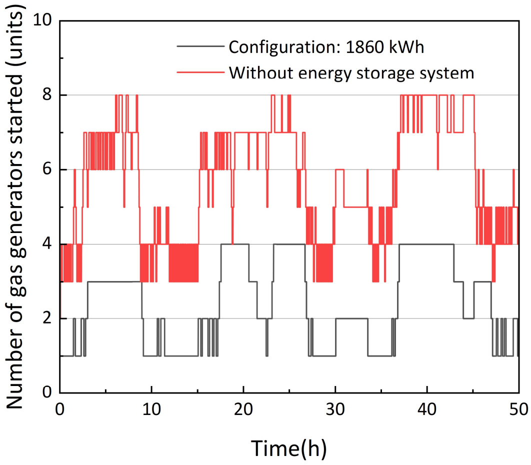

Fig. 9 Comparison of the number of operating gas generators with and without 1870 kWh energy storage

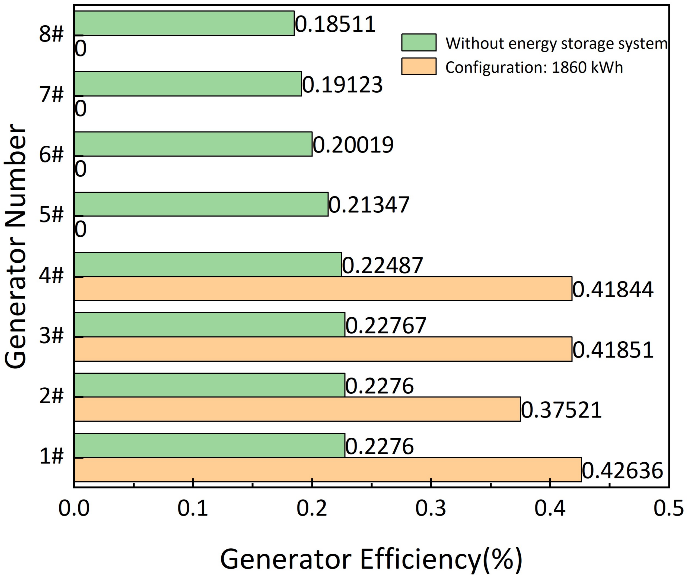

Fig. 10 Average generator efficiency

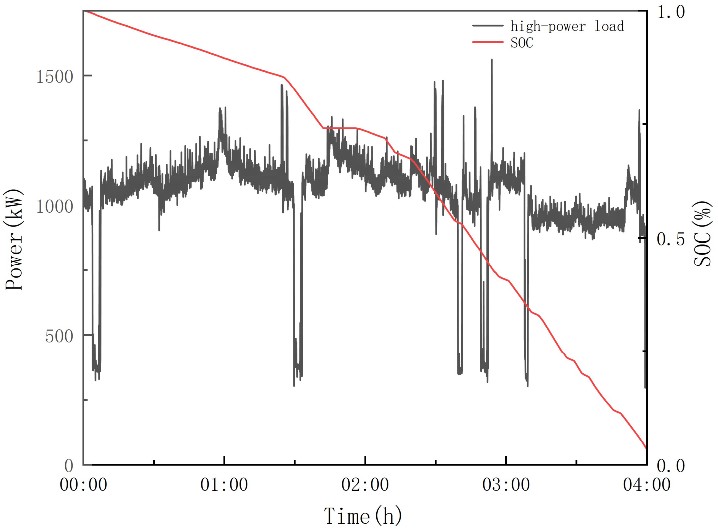

Fig. 11 SOC dynamic response under full battery islanded operation

6. SUMMARY

This study addresses the critical challenges of severe mismatch between gas generator output and highly fluctuating loads, as well as the lack of scientific guidance for the coordinated configuration of energy storage systems. Based on historical load data from a 50DB drilling rig, a gas–energy storage coordinated power supply optimization model was developed, incorporating initial investment costs, operation and maintenance costs, and fuel costs. Through cost–benefit analysis and optimization-based solution methods, the following conclusions are drawn:

(1) The proposed cost optimization model for the gas–energy storage coordinated power supply effectively overcomes the limitations and arbitrariness of traditional experience-based configuration methods. Model-based optimization indicates that the optimal energy storage configuration for the studied drilling crew is 1870 kWh / 992 kW. Compared with commonly adopted empirical configurations of 1000 kWh and 2000 kWh in the industry, this optimized solution achieves significant cost reductions of 15.3% and 13.7%, respectively, thereby demonstrating the scientific validity and superiority of the proposed approach.

(2) The integration of the energy storage system, through peak shaving and valley filling, substantially improves the operating conditions of gas generator units. The results show that the average operating efficiency of the generators can be increased from a maximum of 22.7% to 42.6%, while the required number of operating units is reduced from eight to four. Consequently, equipment utilization and overall system efficiency are significantly enhanced.

(3) Under full-load conditions, the energy storage system is capable of independently supplying power for up to 4 hours, markedly improving power supply reliability and the system’s ability to respond to emergency situations.

By leveraging real operational load data and optimization-based modeling, this study proposes a gas–energy storage coordinated configuration strategy that not only significantly reduces operating costs and improves energy utilization efficiency, but also provides an effective solution and solid theoretical support for achieving an efficient, economical, and environmentally friendly power supply mode in drilling operations.

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