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Comparative performance analysis of two hybrid energy systems for data centers with different replenishment energy sources

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ABSTRACT

With the advent of the digital economy era, data centers are developing rapidly, and energy consumption has become a key factor in their high operating costs. Due to the explosive growth of servers, data centers require more and more power, resulting in power shortages and significant carbon emissions. Using renewable energy to power data centers is a promising solution. In this paper, we compared the performance differences of a hybrid renewable energy system using two different supplemental power sources, natural gas, and conventional diesel, to power a data center. Based on the power required by the data center and the supply of different energy sources, simulations are performed to obtain the system penetration capacity, economic costs, and carbon emissions for comparative analysis. The results show that the system has lower carbon emissions and cost in the natural gas mode, however, the penetration capacity is the same in both modes. With the same battery capacity of 3,000 kWh, the natural gas model costs 0.05 $/kWh less than the diesel model and reduces carbon emissions by 600 tCO_2.

Keywords: distributed energy system, renewable energy, renewable penetration, Levelized Cost of Electricity, carbon emissions

NOMENCLATURE

Symbols	
c	carbon emission factor($kgCO_2/kg$)
CE	carbon emissions (tCO_2)
d	depreciation rate (%)
H_{SL}	hour numbers (h)
LCC	lifecycle cost ($)
$LCOE$	Levelized Cost of Electricity ($/kWh)
N	lifetime (y)
P_{PV}	PV-rated power (kW)
Q_n	annual conversion at year n (kWh)
RP	renewable penetration (%)
V_{FE}	fossil energy consumption (kg)
δ	degradation rate(%)

1. INTRODUCTION

As the global digital economy accelerates, large amounts of data are exchanged inevitably, so large-scale, high-density data centers emerge. There are tens of millions of commercial data centers worldwide, which is expected to double in four years [1]. Data center, not the same as the traditional energy-consuming components, requires continuous operation 24 hours a day, leading to an inevitable increase in energy consumption. According to statistics, global data centers may account for about 1.3% of total electricity consumption in 2010, which grew to 3.5% in 2017 and is still growing, and is expected to account for more than 10% by 2025 [2]. Currently accounting for 3% of total global energy use and 4% of total greenhouse gas emissions [3], the data center industry is becoming one of the largest industrial sectors. Meanwhile, the energy industry is now focused on improving energy efficiency and reducing greenhouse gas emissions. The research on green renewable energy in the energy field has never stopped, and this trend has also gone to data centers with the arrival of cloud computing.

Many scholars have addressed the integrated application aspects of different types of energy. Xuehui Liu et al. [4] proposed a dual-objective data center energy consumption scheduling method considering both electrical energy and natural gas energy and used particle swarm algorithms for simulation scheduling from the perspectives of electrical energy and gas as both energy supply and energy consumption. Yongliang Xie et al. [5] compared hydrogen-powered data center

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and conventional data center configurations and conducted an economic analysis to assess the feasibility of powering the data center with hydrogen energy. Ali Habibi Khalaj et al. [6] utilized on-site hybrid renewable energy generation and storage to minimize the data center's dependence on grid imports and found that grid independence increases as we move away from the equator. Many scholars have also conducted research on the utilization of waste heat in data centers [7,8], mainly focusing on the recovery of waste heat generated in data center servers for supplying heat loads to surrounding residential areas. It is energy reuse that can reduce operating costs.

Many studies have shown that the use of natural gas as a power source can effectively reduce carbon emissions and is more friendly to the environment. Paola Helena Barros Z ´ arante et al.[9] evaluated exhaust emissions of carbon monoxide and carbon dioxide from a natural gas-fueled spark ignition engine. The results show that natural gas significantly reduces carbon monoxide emissions in exhaust gas compared to gasoline. Daniel J.G. Crow et al. [10] found that decarbonizing the upstream component of the natural gas supply chain is achievable using carbon prices similar to those needed to decarbonize the energy system as a whole. Matheus Belucio et al. [11] found that in the short-run, natural gas has a negligible impact on CO_2 emissions when faced with oil consumption by verifying the impact of natural gas on carbon dioxide emissions for a European panel from 1993 to 2018 for sixteen countries.

Currently, a large number of research efforts have focused on determining impact parameters for a renewable energy system. Limited studies have explored the performance of energy supply systems across various energy configurations from a horizontal standpoint. Therefore, in this paper, a cross-sectional comparison is made between a renewable energy system using natural gas (NG) as a supplementary energy source and a system using the diesel model, and both of them are configured with photovoltaic, wind power, and battery storage to meet load requirements. In order to reduce the reliance on traditional fossil energy sources and reduce carbon emissions, the development of green data centers is considered to improve environmental benefits.

2. SYSTEM MODE

2.1 Mathematical Models

Energy system modeling and simulation were based on OptiCE [12] with objective functions consisting mainly of renewable penetration (RP), the Levelized Cost of Electricity (LCOE), and carbon emissions (CE).

RP is one of the most essential factors in a hybrid power system, which is defined as follows:

$$RP = \frac{H_{SL}}{8760} \times 100\%$$

where H_{SL} is the number of hours in a year that the load is met by renewable distributed energy (h).

The LCOE is defined as follows:

$$LCOE = \frac{LCC}{\sum_{n=0}^{N} \frac{Q_n (1-\delta)^n}{(1+d)^n}}$$

where *LCC* is the lifecycle cost of a project (US$); *N* is the lifetime of the project (year); Q_n is the annual production generated in year *N* (kWh), which is taken as 25 years in this case; δ is the degradation rate (%), which is taken as 1%; *d* is the depreciation rate (%), which is taken as 6.8%. Surplus energy is not considered in this study.

The CE is an important indicator for evaluating energy systems which is determined as follows:

$$CE = \frac{cV_{FE}}{1000}$$

where *c* is the carbon emission factor for different fossil energy types (kgCO2/kg); V_{FE} is the fossil energy consumption including gas consumption and oil consumption (kg).

2.2 Calculation Method

In this study two renewable distributed energy systems applied to the data center are compared, using diesel and natural gas as the supplemental energy for the systems. The energy configurations of the two systems are "Diesel-Wind-PV-Battery" mode and "NG-Wind-PV-Battery" mode.

This study uses MATLAB software as a simulation tool based on the OptiCE [12] code, an open-source software package for modeling and optimization of clean energy technologies for the conceptual design of hybrid energy systems. When applied to a data center, a hybrid renewable energy system combining photovoltaic, wind, battery storage, and supplemental energy is considered in the analysis. A total of 8760 hours of operation over a year was calculated using one hour as the simulation interval.

2.3 Parameter Settings

The Meteonorm [13] was used to retrieve the corresponding meteorological parameters in Tianjin of China, such as the hourly values of the wind speed, global horizontal radiation, and diffuse horizontal radiation.

The hourly values of the data center selected in this study are shown in Fig.1. The load on the data center varies due to the amount of data and information stored and the needs of different users, with a maximum of 335 kW. According to this value, a diesel generator and a natural gas turbine with a power of 400 kW were configured for each of the two systems. The characteristic parameters of the PV modules [14] and wind turbines [15] used in the distributed energy system are available on the website. Considering the available area of the data center and the installation conditions of the renewable energy equipment, the PV-rated power was limited to 800 kW. Taking into account the urban landscape where the data center is located and the wind energy potential to avoid negative visual impact from the installation of wind turbines, a 1,000 kW wind turbine has been configured for the system. In addition, battery capacity in the range of 0-6,000 kWh was considered for the configuration.

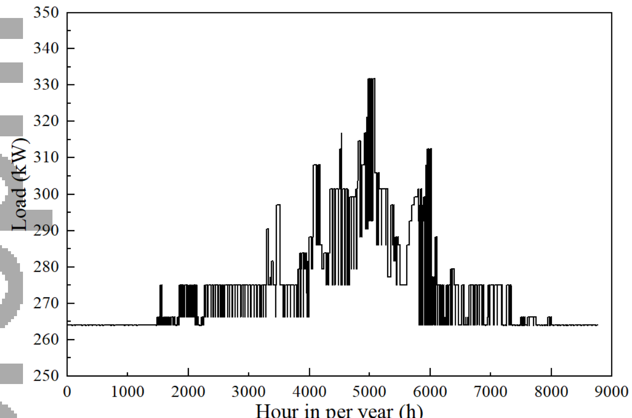

Fig. 1. Hourly values of load for a typical data center.

Finally, the parameters relevant to the economic analysis of the system was listed in Table 1.

Table 1 Main economic parameters of hybrid power system.

Project	Specific initial costs[16-18]	Lifetime
PV power system	1.05[US$/W]	25 y
Wind power system	1.45[US$/W]	25 y
Battery	0.50[US$/Wh]	8 y
Inverter	0.10[US$/W]	10 y
Diesel generator	0.60[US$/W]	8 y
NG turbine	0.58[US$/W]	10 y

3. RESULTS ANALYSIS

3.1 Comparative analysis between system single indicators

Fig. 2 shows the trend of RP with PV-rated power. The RP increases with the increase of PV-rated power. The same law of variation applies to battery capacity. But with the increasing of PV-rated power, the rate of change of RP increases first and then decreases, while it becomes smaller and smaller with the increase of battery capacity. It is clear from the graph that the RP values for both systems are equivalent at the same battery capacity. As the PV-rated power increases from 100 kW to 800 kW, the RP of both systems increases from 11.5% to about 50%. This shows that renewable energy systems using natural gas as a supplemental energy source have no impact on upgrading the RP, without changing the penetration capacity of wind and solar energy. The analysis is mainly due to diesel and natural gas as supplementary energy present in the system, and in the same case, it does not change the amount of solar and wind energy used during the year. The supplementary energy sources are activated only when the renewable

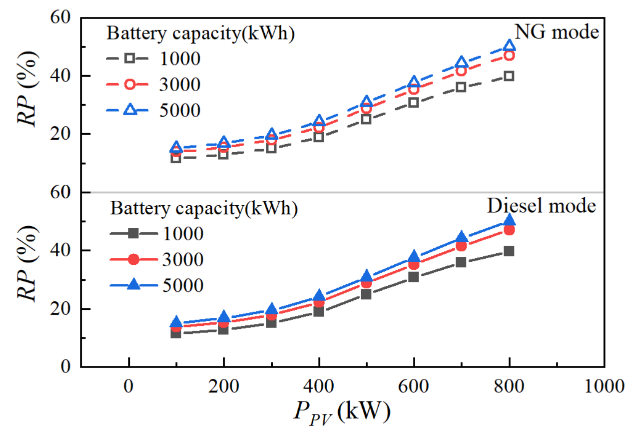

Fig. 2. RP of two-mode hybrid renewable power systems.

energy supply is insufficient and therefore do not change the RP of the system.

Fig.3 shows the trend of LCOE with PV-rated power for two different supplementary energy systems. LCOE decreases with the increasing PV-rated power and the rate of change is increased. While LCOE increases with increasing battery capacity but the rate of change of LCOE is basically the same, with the battery capacity increasing every 2000 kWh, LCOE increase by about

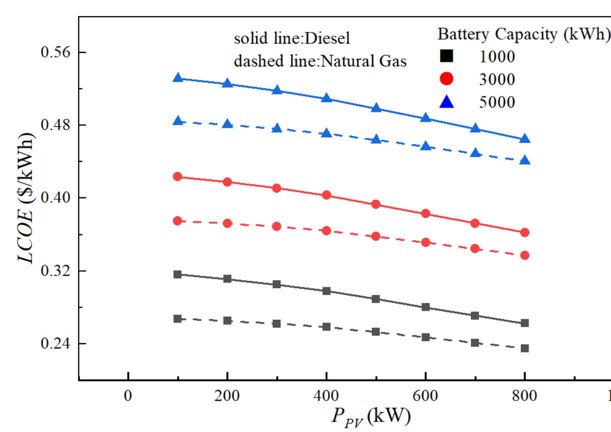

Fig. 3. LCOE of two-mode hybrid renewable power systems.

$ 0.1. It is clear from the graph that for the same battery capacity and PV-rated power, the cost of a system using natural gas as a recharge energy source is significantly lower than that of a system using diesel. For the same battery capacity, a system using natural gas is essentially 0.05 $/kWh less costly than a system using diesel.

According to the former analysis on the RP and LCOE the rate of change of RP and LCOE with battery capacity, a battery capacity of 3000 kWh was chosen for the carbon emission analysis. It should be noted that the carbon emissions mentioned in this study refer to operational CO_2 emissions, and we did not perform any life cycle analysis. The trend of carbon emissions with PV capacity for both systems is shown in Table 2. The CE decreases with the increase in PV-rated power. And for the same system, the CE reduction is about the same for every 100 kW increase in PV-rated power. It is obvious from the figure that the system using diesel as supplementary energy has much higher CE than that using natural gas. Since natural gas is a much cleaner energy type compared to diesel, for the same parameters, the difference in carbon emissions between the two systems is about 600 tCO_2. Therefore, the advantages of using natural gas as a rechargeable energy source to gradually replace traditional fossil energy sources such as diesel for energy supply are more obvious.

Table 2 CE of two-mode hybrid renewable power systems.

Parameter	Unit	Value			
PV rated power	kW	100	200	300	400
CE of Diesel mode	tCO_2	2130	2023	1908	1780
CE of NG mode	tCO_2	1541	1461	1377	1284
PV rated power	kW	500	600	700	800
CE of Diesel mode	tCO_2	1637	1498	1368	1250
CE of NG mode	tCO_2	1181	1081	987	903

3.2 Synergy comparison analysis among system indicators

The RP versus LCOE for both hybrid systems is shown in Fig.4. For the renewable energy supply system the lower the cost and the higher the RP the better the system performance. Therefore, in Fig.4 the closer the point to the upper left corner, the better it is, and the closer the point to the lower right corner, the less desirable it is. The natural gas systems are closer to the left side than the diesel systems for all three battery capacities. It is clear that the performance of the system using natural gas with the same parameters is much better than that of the system using diesel. The previous analysis of the impact of PV-rated power growth on the rate of change of RP and LCOE can also be corroborated in Fig.4. The advantages of using natural gas as a recharge energy source are further confirmed by the analysis of the system performance.

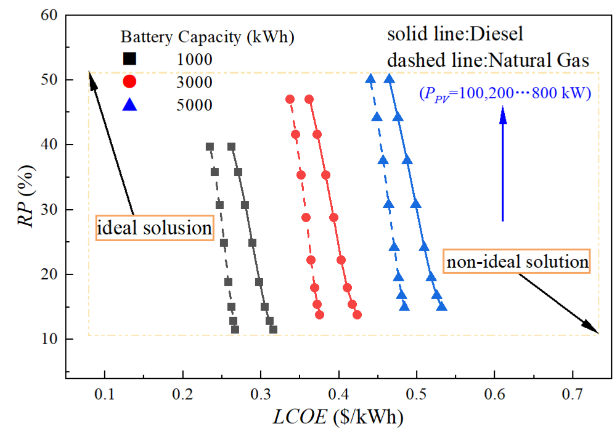

Fig. 4. RP versus LCOE for two-mode systems.

In addition, the synergy analysis between the parameters of the two systems was further analyzed at a battery capacity of 3000 kWh. The corresponding RP and reduced CE compared to the diesel mode are shown in Fig.5, while the LCOE and the reduced LCOE percentage are shown in Fig.6. According to Fig.5, although the RP values are the same in both system modes, the carbon emissions in the natural gas mode are reduced by more than 27.5% relative to the diesel mode, which has good environmental benefits. The carbon reduction in the natural gas model tends to increase and then decrease with the increase of PV-rated power, and the best carbon reduction is achieved at the PV-rated power of 400 kW. However, on balance, a PV-rated power of 400 kW has a slight 0.1% carbon reduction advantage compared to 800 kW, but the RP is about 25% lower than it. Therefore, it is better to use 800 kW PV-rated power to achieve better environmental benefits and system performance.

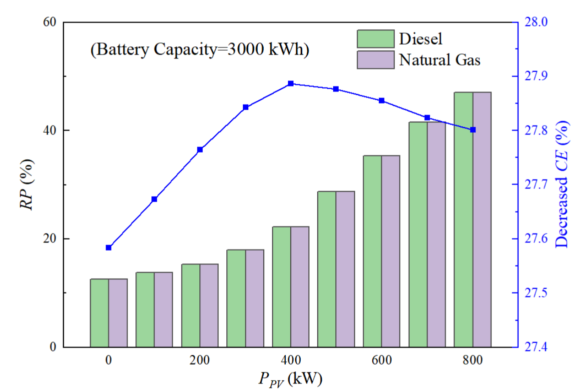

Fig. 5. RP and decreased CE for two-mode systems.

According to Fig.6 the cost of natural gas mode compared to diesel mode is reduced by more than 7 percentage points, and with the growth of PV-rated power decreased LCOE is getting smaller. The main reason is that with the increase of PV-rated power the solar energy available to the system increases, renewable energy basically meets the energy demand, the frequency of starting supplementary energy decreases, and the amount of supplementary energy consumed in the system decreases, so the cost of natural

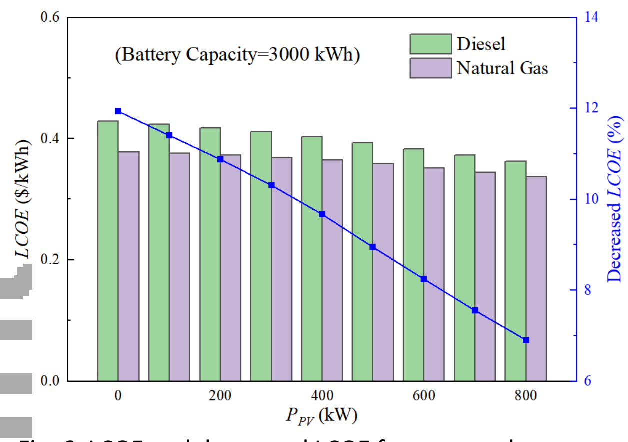

Fig. 6. LCOE and decreased LCOE for two-mode systems.

gas is not significantly reduced compared to diesel.

4. *CONCLUSIONS*

This paper compares two hybrid energy systems (diesel and natural gas used for recharge energy) for data centers in terms of economic cost, system performance, and carbon emissions. The main findings of this study are summarized below:

Comparing the impact parameters of the system longitudinally, the RP value shows an increasing trend with the increase of PV-rated power and battery capacity. However, the rate of change with PV is increasing and then decreasing, while the rate of increase with battery capacity is gradually decreasing. Unlike the equal increase of LCOE with battery capacity, the rate of change with PV is accelerated. When the PV-rated power increases, the carbon emission decreases gradually.

In a cross-sectional comparison between the two systems, it was found that the RP values of the two systems are consistent since the RP is only related to the amount of renewable energy utilized in the operation of the system. The LCOE in NG mode is lower than in diesel mode and the difference is about 0.05 $/kWh at the same battery capacity. The CE in natural gas mode is also lower than in diesel mode, and the difference is about 600 tCO_2 for a 3000 kWh battery capacity because natural gas is a cleaner energy source than diesel.

Compared with diesel mode, the natural gas mode can achieve lower LCOE and higher RP with the same parameters, and the system performance is better. And the natural gas model can reduce the CE by more than 27.5 percentage points, and the carbon emission reduction increases and then decreases as the PV-rated power increases, reaching the lowest CE at 400 kW, but combined high RP and low CE the 800 kW PV-rated power is better. The LCOE of the natural gas model can be reduced by more than 7 percentage points, and the reduction in LCOE decreases gradually as the PV-rated power. However, the PV-rated power chosen for the natural gas model to achieve both low carbon emissions and low LCOE is contradictory, so the optimization results need to be further considered to find the optimal PV capacity in future work.

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DECLARATION OF INTEREST STATEMENT

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

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