DISTRIBUTED MULTI-ENERGY SYSTEMS CONSIDERING POWER-TO-X TECHNOLOGY: PLANNING, SCHEDULING, AND PERFORMANCE ASSESSMENT

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ABSTRACT

The distributed multi-energy systems place emphasis on the complementary and local application of heterogeneous energy sources, and power to methanol process can be coupled, reducing carbon emissions while increasing the profitability. For providing an economical and low-carbon solution, a real community energy system integrated with solar energy and natural gas has been investigated in this work. Aimed at the minimization of the daily cost referring to the net expenditure after considering the offsetting benefits, the carbon capture, water electrolysis, and methanol synthesis are combined, with the methanol and oxygen exported as products. The capacity planning and operation scheduling have been performed, and the results indicated that the daily cost can be reduced by 69.67% compared to the conventional energy supply after the scheduling optimization. In the case scenario and typical day, the production of methanol and oxygen is 6.30 t and 13.49 t based on an electricity demand of 28.78 MWh and a heat demand of 11.85 MWh. Due to the contribution of carbon capture, the purchase of 5.90 t of carbon allowances is avoided and instead there are 3.86 t of allowances available for sale. Besides, the effect of device capacity and operating parameters on economics has been discussed. This study could help to promote the application of power to methanol in distributed energy systems.

1 INTRODUCTION

One of the most severe global challenges nowadays is the climate warming, and there are continual advocates for energy conservation and emission reduction (Zhang and Zhang, 2020). In order to limit the ecological degradation caused by increasing CO_2 emissions, the sustainable solutions that promote carbon neutrality need to be devised. The keys to meeting this challenge are to expand the penetration of renewable energy and capture CO_2 (Peixoto *et al*., 2024). Due to the inherent volatility and intermittent nature of renewable energy, the conversion of it into hydrogen energy through the electrolysis of water has been vigorously pursued as an ideal mode for reducing energy waste and facilitating the energy transformation (Shin *et al*., 2023). However, until infrastructure such as an extensive hydrogen pipeline network and large-scale cheap hydrogen storage is completed, the costs of hydrogen storage and transportation will be prohibitive, which may suppress the demand for hydrogen and hinder the path to scalable utilization. Power-to-X technology is a potential and promising solution to solve this dilemma. By coupling with other synthesis processes, hydrogen energy is converted into other chemical energy sources, such as methanol, for convenient storage and utilization (Fogel *et al*., 2024).

Pratschner *et al.* (2023) paid attention to an energy hub including green energy, a biomass plant in which CO_2 in the flue gas is captured, and a power to methanol process. The basic techno-economic indicators of the case system were analyzed in detail. Lee *et al.* (2020) studied the optimization operation of power to methanol by the simulation of technological process, and conduced the predictive cost analysis to achieve a promising economics. Zhang *et al.* (2023) proposed a biomass-based combined heat and power system integrating with methanol synthesis, using syngas from biomass gasification and hydrogen from water electrolysis, which can raise the energy efficiency and lead to a shorter payback time. Turgut and Dincer (2023) designed a geothermal energy utilization system to produce methanol

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with electricity and freshwater, and the thermodynamic analysis results demonstrated the energy and exergy efficiencies can reach 36.96% and 39.31%, respectively. Lonis *et al.* (2021) assessed an energy system including the production and utilization of renewable methanol, the solid oxide fuel cell and organic Rankine cycle were considered, and concluded that the power-to-methanol efficiency can reach about 70%. Khan *et al.* (2024) conducted the thermodynamic and economic analysis of a solar-assisted co-electrolysis of H_2O and CO_2 system for methanol production, and discussed the sensitivity of key parameters. Sollai *et al.* (2023) carried out the comprehensive process simulation by means of Aspen Plus software to evaluate the techno-economic of methanol production from carbon dioxide and hydrogen.

The distributed energy system has the characteristics of multi-energy complementary, close to the user, the low pollution and high efficiency (Wang *et al*., 2022). As the power system gradually transforms from large base and large network to parallel with microgrid, the distributed energy systems are being built on a growing scale. For actively promoting the development of multi-energy complementary clean energy bases, optimizing scientifically the structure and configuration of power supply is quite necessary (Di *et al*., 2023). It is of great significance to work on the planning, scheduling, and performance assessment of the systems under different scenarios.

Currently, there is a lack of discussion that combines power to methanol technology into the distributed energy systems for improving economic and environmental performance, and this work contributes to fill this gap. Based on a real community powered synergistically by natural gas and solar energy, a low-carbon and economic prosumer has been built. The process of separating CO_2 from the air is avoided by obtaining the carbon source from the CO_2-enriched gas turbine exhaust flue through a carbon capture system. CO_2 reacts chemically with hydrogen produced by electrolyzing water to synthesize methanol. The economic optimization has been collaboratively performed to rationalize the capacity allocation and scheduling of energy devices. Through the hourly simulation, the proposed system has been comprehensively analyzed. This work may help develop distributed energy systems aimed at a clean and economic alternative.

2 METHOD

2.1 System description

Currently, the conventional municipal distributed energy systems usually use solar energy and natural gas as energy sources to meet the electricity and heat needs of a community. Photovoltaics (PV) and gas turbines (GT) are combined to provide electricity, with the unmet portion being supplemented by the public grid. The exhaust flue gas from the GT is vented to a heat-recovery boiler (HB), which is assisted by a gas boiler (GB) for heat supply. Batteries (BT) and hot-water tanks (HT) are adopted for the electrical and thermal energy storage, respectively. The power to methanol module has been added in the proposed system compared to the reference system. The flue gas from the HB enters the carbon capture system device (CCS) to achieve carbon enrichment driven by heat. Water electrolysis takes place in the electrolyzer (EL) where hydrogen and oxygen are generated at the cathode and anode respectively. Hydrogen and carbon dioxide are compressed to the required pressure and fed into the methanol reactor (MR). It is worth noting that all the captured CO_2 is used to produce methanol, so its storage need not be considered. Methanol and oxygen can be profitably exported as by-products to meet the needs of industry. Under current market conditions and technological maturity, the cost of transporting hydrogen in a high-pressure trailer is approximately 1156.47 $/t, while the cost of transporting methanol is 57.82 $/t, and there is a significant difference between the two. The energy flows of the main devices are displayed in Figure 1, and the technical and economic parameters of the basic devices are taken from the manufacturers and the market, depicted in detail in previous publications (Xue *et al*., 2023).

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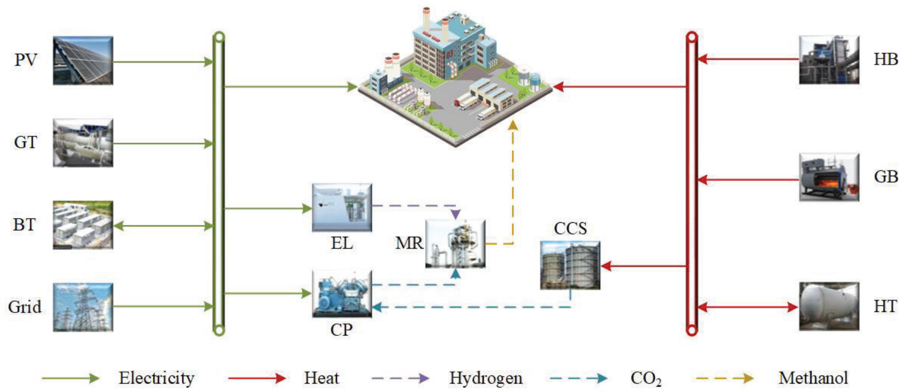

Figure 1: Energy flows of the proposed system

2.2 Objective function

The daily cost (C_d, \$) has been selected as the objective function in the scheduling process, which includes the daily expense and the daily revenue, as formulated by equation (1). The former covers the daily device investment (C_{dv}, \$), administrative cost (C_{ad}, \$), operational cost (C_{op}, \$), maintenance cost (C_{mt}, \$), depreciation cost (C_{dp}, \$), and carbon trading cost (C_{ct}, \$), and the latter consists of the benefits from green certificate trading (C_{gc}, \$), methanol sales (C_{me}, \$), and oxygen sales (C_{ox}, \$).

$$C = C_{\mathrm{dv}} + C_{\mathrm{ad}} + C_{\mathrm{op}} + C_{\mathrm{mt}} + C_{\mathrm{dp}} + C_{\mathrm{ct}} - C_{\mathrm{gc}} - C_{\mathrm{me}} - C_{\mathrm{ox}} \tag{1}$$

The individual calculations are listed by equation (2)-(10):

$$C_{\mathrm{dv}} = \frac{i \cdot (1+i)^l \cdot (1+f_{\mathrm{aux}})}{N_{\mathrm{d}} \cdot \left[(1+i)^l - 1\right]} \cdot \sum C_\alpha \tag{2}$$

$$C_{\mathrm{ad}} = \frac{f_{\mathrm{ad}} \cdot (1+f_{\mathrm{aux}})}{N_{\mathrm{d}}} \cdot \sum C_\alpha \tag{3}$$

$$C_{\mathrm{op}} = \sum_{t=1}^{24} \left[up_{\mathrm{ng},t} \cdot \left(V_{\mathrm{GT},t} + V_{\mathrm{GB},t}\right) + up_{\mathrm{grid},t} \cdot E_{\mathrm{grid},t} \right] \tag{4}$$

$$C_{\mathrm{mt}} = \frac{f_{\mathrm{mt}} \cdot (1+f_{\mathrm{aux}})}{N_{\mathrm{d}}} \cdot \sum C_\alpha \tag{5}$$

$$C_{\mathrm{dp}} = \frac{(1+f_{\mathrm{aux}}) \cdot (1-f_{\mathrm{dp}})}{l \cdot N_{\mathrm{d}}} \cdot \sum C_\alpha \tag{6}$$

$$C_{\mathrm{ct}} = \sum_{t=1}^{24} \left[up_{\mathrm{C}} \cdot \left(e_{\mathrm{tot}} - e_{\mathrm{alw}}\right) \right] \tag{7}$$

$$C_{\mathrm{gc}} = up_{\mathrm{gc}} \cdot \sum_{t=1}^{24} E_{\mathrm{PV},t} \tag{8}$$

$$C_{\mathrm{me}} = up_{\mathrm{me}} \cdot \sum_{t=1}^{24} m_{\mathrm{me},t} \tag{9}$$

$$C_{\mathrm{ox}} = up_{\mathrm{ox}} \cdot \sum_{t=1}^{24} m_{\mathrm{ox},t} \tag{10}$$

where i denotes the interest rate; l represents the lifecycle; f_{aux} is auxiliary cost ratio; N_d denotes the number of hour in a day; C_α is the purchase cost of energy device, calculated by the size and unit price

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of each device, as shown in Table 1, \$; f_{ad} is administrative cost ratio; $up_{\mathrm{ng},t}$ and $up_{\mathrm{grid},t}$ are unit prices of natural gas and electricity at hour t, \$/m^3, \$/kWh; $V_{\mathrm{GT},t}$ and $V_{\mathrm{GB},t}$ respectively denote the natural gas consumed by GT and GB at hour t, m^3; $E_{\mathrm{grid},t}$ is electricity purchased at hour t, kWh; f_{mt} and f_{dp} represent maintenance and depreciation cost ratio, respectively; up_{C} is unit trading price of carbon allowance, \$/t; e_{tot} and e_{alw} are the total carbon emissions and carbon allowance, t; up_{gc} is the unit trading price of green certificate, \$/pcs; $E_{\mathrm{grid},t}$ is electricity supply of PV at hour t, kWh; up_{me} and up_{ox} are the prices of methanol and oxygen, taken as 404.76 and 65.05 \$/t respectively; $m_{\mathrm{me},t}$ and $m_{\mathrm{ox},t}$ are the methanol and oxygen production at hour t, t.

Table 1: Unit prices of energy devices

Device	**PV**	**GT**	**GB**	**HB**	**BT**
Unit price	66.50 \$/pcs	1358.85 \$/kW	43.37 \$/kW	28.91 \$/kW	115.65 \$/kW
Device	**HT**	**AE**	**CCP**	**HCP**	**MR**
Unit price	14.60 \$/kW	216.84 \$/kW	235.24 \$/(kg/h)	17800 \$/(kg/h)	369.13 \$/(kg/h)

3 CASE STUDY

3.1 Scenario

A real community located in northern China has been chosen as the case study for this work, which includes residential areas, office buildings and small industrial plants. The local area is a solar-rich region with abundant natural gas. The climate is typically temperate continental, and the weather conditions and load demand on a typical day are presented in Figure 2. The daily total electricity and heat demands 28.78 MWh and 11.85 MWh, respectively. Table 2 lists the dimensions of energy resource and energy storage devices. The top of the buildings is arranged with 5600 PV modules, each module is 0.46 kW, and a 1 MW GT is equipped as the prime mover. BT is equipped with 20% of the PV capacity and the duration of energy storage is set as 2 hours. Besides, 1 MWh of HT is used for heat storage. The time-of-use price mechanism is applied by the local grid, as shown in Table 3.

Table 2: Dimensions of energy resource and energy storage devices

Device	**PV**	**GT**	**BT**	**HT**
Capacity	2576 kW	1000 kW	1030 kWh	1000 kWh

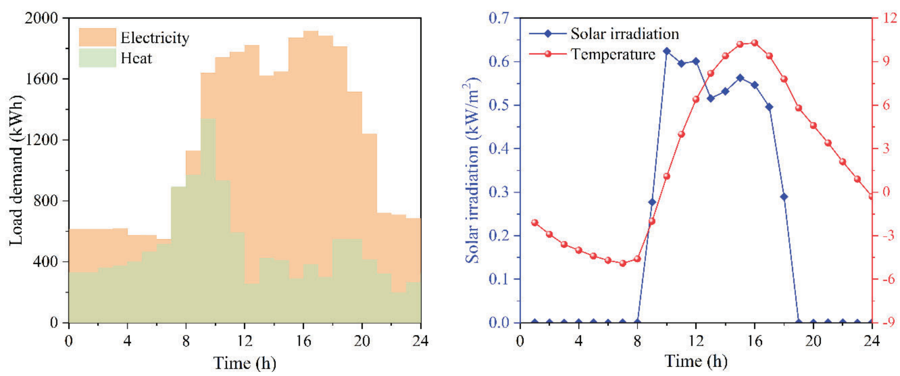

Figure 2: Load demand and meteorological data

Table 3: Time-of-use prices of the grid

Time (h)	**0:00-7:00 23:00-24:00**	**7:00-8:00 12:00-18:00**	**8:00-11:00 19:00-23:00**	**11:00-12:00 18:00-19:00**
Price (\$/MWh)	32.68	83.41	134.14	108.77

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3.2 Planning results

Based on the capacity and input parameters of the existing devices, the proposed system is economically scheduled using the GUROBI solver based on MATLAB platform to obtain the optimal capacity of the heating devices and power to methanol module, and the results are shown in Table 4. At this planning, the daily cost of the proposed system is 629.49 $, which is 69.67% lower compared to 2075.52 $ of the reference system.

Table 4: Capacity planning results of devices

Device	GB	HB	AE	CCP	HCP	MR
Capacity	0.24 MWh	1.32 MWh	0.36 MWh	0.60 t/h	0.08 t/h	0.31 t/h

The expenditures and revenues for the reference system and the proposed system are displayed in Figure 3, with positive values indicating expenditures and negative values indicating revenues. The total initial investment of the proposed system has a growth compared to the reference system because of the addition of new devices. By annualizing the investment and then amortizing it to each day, the daily device cost rises from 397.79 $ to 774.96 $. Correspondingly, the administrative cost, maintenance cost and depreciation cost have increased. The water electrolysis and gas compression processes both consume electricity, and the carbon capture process requires heat, which results in a significant increase in the energy consumption level of the system, and a considerable increase in the operational cost, with natural gas cost and electricity purchase cost growing by 1217.66 $ and 95.18 $, respectively. However, the carbon trading cost changes from 51.15 $ to a profit of 33.46 $, which is attributed to the role of carbon capture. In addition, the production of methanol and oxygen in the typical day is 6.30 t and 13.49 t, respectively, which brings the benefits of 2548.60 $ and 877.71 $, respectively. The green certificate gains are consistent in both systems.

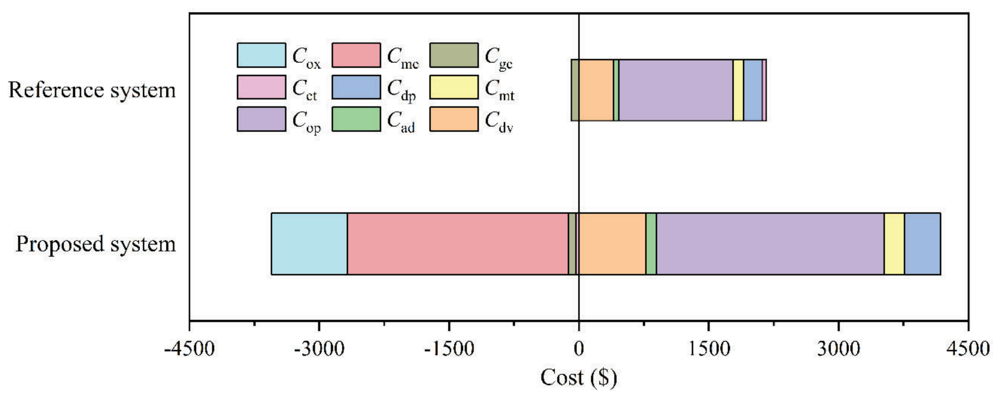

Figure 3: Economic comparison results

According to the analysis of economy, the introduction of the power to methanol module has changed the purchase of carbon allowance into a profitable sale, as shown in Figure 4. The owner varies from a buyer to a seller in the carbon trading market, and satisfies the environmental supervision of the government, which is the contribution of carbon capture. In the reference system, the combustion of natural gas in GT and GB produces 6.03 t and 0.66 t of CO_2, respectively, and the carbon allowances receive total 4.22 t. The electricity purchase from the grid corresponds to an indirect carbon emission of 3.43 t, which results in the demand to purchase as much as 5.90 t of carbon allowance from the carbon trading market. For the proposed system, the combustion of natural gas in GT and GB can produce 13.74 t and 0.32 t of CO_2, respectively, and after considering the role of CCS, the carbon emission from GT is only 1.37 t. The indirect carbon emission of purchasing electricity from the grid is 2.85 t, and the system receives 8.41 t of carbon allowances at this time, thereby 3.86 t of carbon allowance can be sold.

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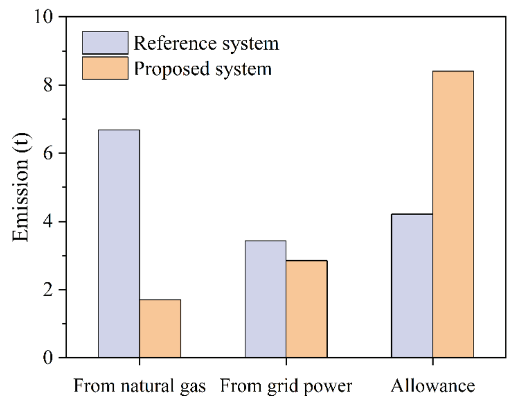

Figure 4: Carbon emission comparison results

3.3 Scheduling on a typical day

The electrical and thermal balances of the reference and proposed systems on the typical day are shown in Figure 5. The top of the horizontal axis indicates the energy output of devices and the bottom indicates the different energy demands. In the reference system, GT is maintained to operate at the lowest partial load rate during the early morning hours due to the low electricity price, and the rest of the electricity demand relies on purchasing from the grid. When the price of electricity is higher, GT generates electricity instead of buying electricity. It is worth noting that PV electricity has the highest priority. The base heat load is met by HB and supplemented by HT and GB depending on the change in the heat supply-demand balance. In the proposed system, the energy consumption of the power to methanol module increases both the electrical and thermal loads in the community and the supply and demand relationship becomes more complex. In order to maximize the benefits of methanol and oxygen, GT is operated at full load during the hours of low solar conditions, and more CO_2 can be captured and used to generate methanol while the carbon emissions of the system are reduced and the environmental friendliness is greatly improved. It is because of the high load of GT that the HB heating capacity is greatly increased, which results in a considerable reduction in GB utilization.

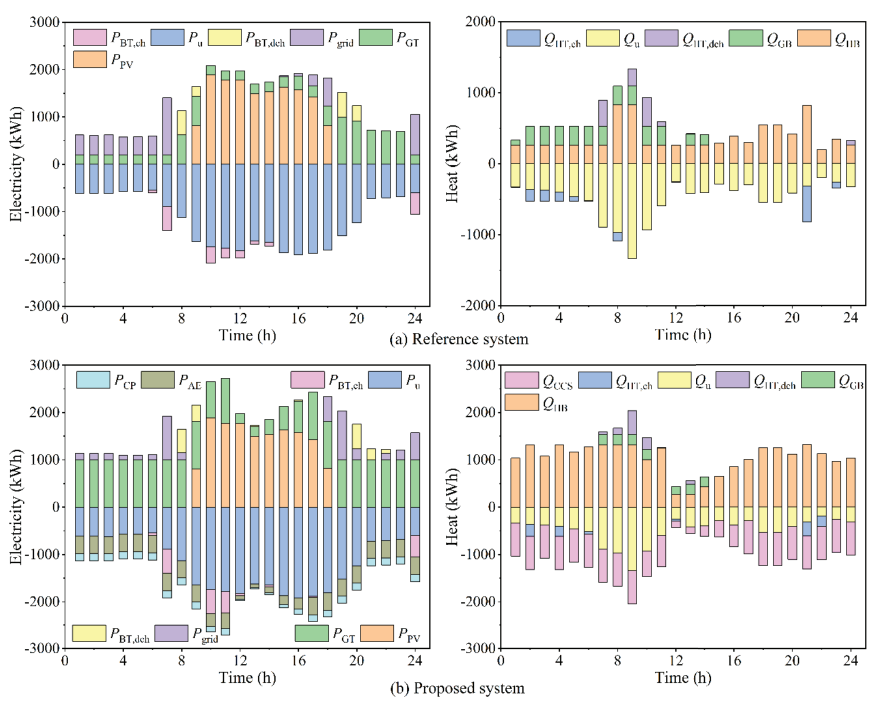

Figure 5: Scheduling results on the typical day

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3.4 Performance assessment

The changes in the capacity of the main devices and key operating parameters result in varying degrees of changes in the objective function. Increasing or decreasing the capacity of PV and GT by 5% and 10%, respectively, and changing the carbon capture efficiency and methanol synthesis efficiency from 70% to 90%, the variations in the daily cost are shown in Figure 6. With the increase of PV capacity, the daily cost has an upward trend, which is due to the increase of PV investment cost and the corresponding increase of maintenance and administrative costs, and at the same time, the use of GT is reduced, the amount of methanol synthesized and the profit decrease. The trend of daily cost with GT capacity is opposite to that of PV, although the change is relatively small. When the capacity of PV and GT decreases by 10%, the daily cost decreases by 21.31% and increases by 5.50%, respectively; when the capacity of PV and GT increases by 10%, the daily cost is 821.07 $ and 601.86 $, respectively. When the carbon capture efficiency decreases from 90% to 70%, the daily cost will be significantly higher by 76.17%, which is owning to the fact that the methanol production decreases with the decrease of carbon capture efficiency. The effect of methanol synthesis efficiency on the daily cost has a similar pattern, when the methanol synthesis efficiency increases from 70% to 90%, the daily cost of 630.47 $ can be turned into a net income of 84.25 $, which has a very favorable economy.

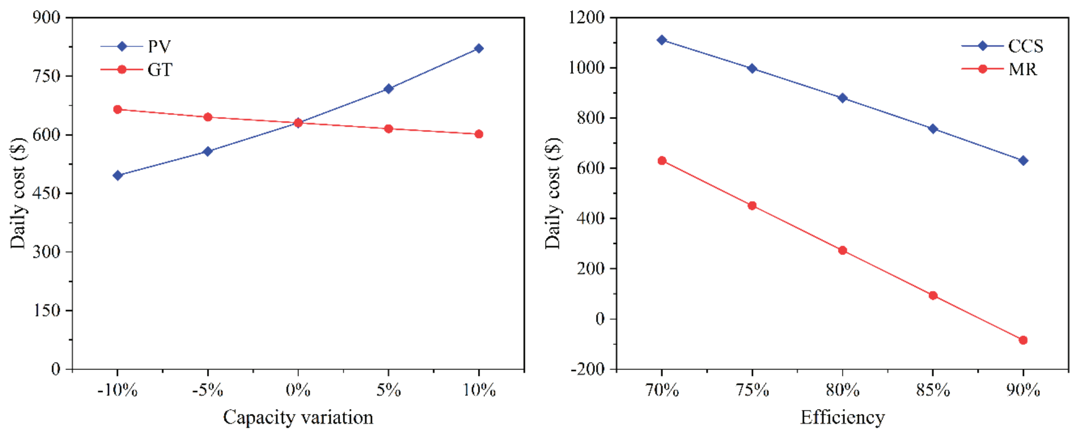

Figure 6: Sensitivity results of key parameters

4 CONCLUSIONS

A novel distributed energy system integrated with power to methanol has been designed and optimized for better economic and environmental performance. Considering the time-of-use prices of electricity alongside the trading of carbon and green certificate, the optimal energy supply has been realized through hourly scheduling. A real community has been selected for the case study, and the main conclusions are as follows:

- Though the scheduling optimization of the proposed system, the daily cost can be reduced by 69.67% compared to the conventional energy supply system. The daily production of methanol and oxygen is 6.30 t and 13.49 t under the electricity demand of 28.78 MWh and the heat demand of 11.85 MWh, and the economic potential has been further improved.
- Due to the contribution of carbon capture, the purchase of 5.90 t of carbon allowances is avoided and instead there are 3.86 t of carbon allowances available for sale, which is much more environmentally friendly.
- The daily cost increases with PV capacity and decreases with GT capacity, with the former varying more. In addition, the daily cost has a decreasing trend with both carbon capture efficiency and methanol synthesis efficiency.

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NOMENCLATURE

Abbreviation

BT	battery
CCP	carbon dioxide compressor
CCS	carbon capture
CP	compressor
EL	electrolyzer
GB	gas boiler
GT	gas turbine
HB	heat-recovery boiler
HCP	hydrogen compressor
HT	hot-water tank
MR	methanol reactor
PV	photovoltaics

Symbol

C	cost	(US$)
e	carbon emission	(t)
E	electricity	(kWh)
f	ratio	(-)
i	interest rate	(-)
l	lifecycle	(year)
m	mass	(t)
N	number	(-)
up	unit price	($/m^3, $/kWh, $/t)
V	volume	(m^3)

Subscript

ad	administrative
alw	carbon allowance
C	carbon
ct	carbon trading
d	day
dp	depreciation
dv	device
gc	green certificate
grid	public grid
me	methanol
mt	maintenance
ng	natural gas
op	operational
ox	oxygen
t	tth hour
tot	total
α	αth device

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