KANG, Jing; WANG, Shengwei; GANG, Wenjie. Performance of distributed energy systems in buildings in cooling dominated regions and the impacts of energy policies. Applied Thermal Engineering, 2017, 127: 281-291.

https://doi.org/10.1016/j.applthermaleng.2017.08.062

Performance of Distributed Energy Systems in Buildings in Cooling Dominated Regions and the Impacts of Energy Policies

Jing Kang[1], Shengwei Wang[1,2]* and Wenjie Gang[1,3]

[1] Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[2] Research Institute for Sustainable Urban Development, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[3] Department of Building Environment and Energy Engineering, Huazhong University of Science and Technology, Wuhan, China

Abstract: The distributed energy system (DES) is an energy efficient and economical alternative to the centralized energy system (CES). However, quantitative performance assessment, the influential factors and the impacts of energy policies in cooling dominated regions are still not well studied. This paper therefore presents an investigation on the building integrated DES in Hong Kong, a typical city with cooling demand year-around. Considering the characteristics of the energy demands, DESs, which integrate distributed generations, chillers and the utility grid, are designed. The performance of DESs in buildings is tested on a simulation platform using dynamic models. The primary energy saving and the payback period are estimated. The impacts of major design parameters and energy policies on the DES performance are studied. Results show that DESs achieve energy saving only when integrated in large-scale buildings of certain functions. Moreover, the performance can be improved by optimizing the equipment capacities. The comparison between two different energy policies with respect to the grid interaction illustrates that DESs can achieve better performance when selling electricity is permitted. The gas price has very significant impacts on economic benefits of DESs and the current market gas price could allow cost-effective application in some circumstances.

Keywords: Distributed energy system, building energy, primary energy saving, performance assessment, influential factors.

** Corresponding author: Shengwei Wang, email: beswwang@polyu.edu.hk*

1 Introduction

Due to the expected increase in primary energy consumption and a rapid rise in green-house gas emissions, the notion of energy systems with higher energy efficiency and less pollutant emission has been attracting increasing attention [1]. The distributed energy system (DES), which integrates distributed energy supply equipment and/or the utility grid can be an innovative energy supply system with prospective development and benefits [2]. Unlike centralized energy systems (CESs), which used centralized power plants for electricity generation, on-site generations in DESs supply power to end users without long distance transmission and power loss for the network resistance and the voltage transformation. By using renewable or low-carbon energy resources, DESs can produce less pollution while satisfying energy demands. Moreover, DESs improve the energy conversion efficiency by cascade utilization of energy, for example, the generated electricity of on-site generations can be used directly and then lower temperature exhaust gas (from on-site generations) is further used for heating or cooling [3].

Generally, the DES uses distributed generations, like solar panel, wind turbines, geothermal energy production and gas engine, for power generation, and thermal producers for heating or cooling. Recent research denoted that an appropriately designed DES has a number of advantages compared with the CES in aspects of energy efficiency and economic benefits [4]. However, not every technique can achieve those benefits without any application limit. For example, because of the low efficiency and large installation area, renewable energy integrated DES is proposed to be utilized in rural areas or places where the building density is not high [5].

The multi-generation system, also called CCHP (combined cooling, heating and power), is a DES technique with high efficiency. It uses distributed generations (gas turbines or engines) to produce electricity, and recovers the waste heat for heating or cooling simultaneously [6]. Due to its high energy efficiency (usually above 80%) and high stability in energy supply, the multi-generation system received more attentions than renewable energy resources in DESs application, especially in urban areas [7, 8]. Many studies on DESs have been done worldwide, such as USA, European countries, Japan, China and India. Those studies include systematic performance assessment, the feasibility in various situations, design optimization and control optimization. The system performance assessment is important because it not only shows the advantages of this technology directly, but also gives decision makers meaningful advices for future planning. Fumo et al. introduced the basic numerical models and analysis method in multi-generation system study, and evaluated the performance of DESs for large office buildings under various operation strategies in Chicago [9, 10]. Compared with the CES, the DES can save 15.9% of annual primary energy consumption under an appropriate operation strategy. The climate can affect the users' energy demand profile and then the performance of DESs. Wu et al [11] compared the DES performance among various climate conditions and indicated this system can obtain more benefits in hot summer and cold winter zone in Japan. Cho et al. [12] highlighted the advantages of DESs particularly in the cases where the duration having thermal energy demands is long. Li et al. [13] used heat-to-electricity ratio and energy saving rate to decide potential users and application boundaries in different climate zones. Results show that the DES application boundary can be wider with higher heating demand. In addition, the energy policy is another significant factor affecting the planning and decision making of DESs. Available energy policies increase the penetration of DES technologies and encourages the adoption of on-site generations [14]. According to Bush et al., the feed-in tariff scheme can improve the efficiency and economic benefits of small-scale renewable and low carbon non-renewable generation technologies in DESs [15]. Zheng et al. [16] investigated the effects of three different feed-in tariff policies on DES performance. The results demonstrated that both system energy and economic performance were improved if the surplus electricity could be sold with a favorable price. However, the impacts of energy policies on the application of DESs in specific climate zones are rarely analyzed.

The cooling dominated region, usually located in tropical or subtropical zones, is a region where cooling is required almost all the year, and demands of space heating is negligible. Many studies focus on the DESs, which include distributed generations, heating components (e.g., waste heat exchangers) and cooling components (e.g., absorption chillers), for regions where both space heating and cooling are needed. However, the feasibility and the performance of DESs, which usually include distributed generations and chillers, in cooling dominated regions are rarely investigated yet. A comprehensive study, including system modelling, performance assessment and influential factors analysis, on DESs in this region is essentially needed. To reduce CO_2 emission and meet the increasing electricity demand, the government in Hong Kong, a typical cooling dominated city, has set it policy to replace coal gradually by natural gas as primary energy in power generation. The natural gas, a clean and low-carbon primary energy, is able to be utilized as energy resources in centralized power plants or delivered to users for on-site generation. This provides an opportunity for the application of DESs.

This study therefore aims to investigate the feasibility and performance of building integrated DESs in cooling dominated regions. An appropriate DES configuration is selected based on the characteristics of electricity and cooling demands. The detailed DES models are developed. Appropriate operation strategies based on energy policies are adopted to control the coupling operation among energy supply systems. The primary energy saving and payback period are used as the energy and the economic assessment criteria. The DES performance and the impacts of influential factors, including major design parameters and energy policies, are investigated and analyzed. The suggestions for DESs application in cooling dominated regions are summarized.

2 Methodology and major steps of performance assessment

To investigate the performance of DESs in cooling dominated regions, the following methodology is adopted in this study. Three major steps are involved, including: system design, system modelling and performance assessment as shown in Fig. 1. Each step is explained in detail as follows.

2.1 *System design*

i. Collecting the building information B (x_1, x_2… x_n) and the outdoor weather parameters W (y_1, y_2… y_n). B includes the building function, building physical parameters, the indoor environment settings, etc. W includes the outdoor temperature, the relative humility, etc.

ii. Predicting the energy demands of the building. The electricity demand (E_d, excluding that for cooling) profile and cooling demand (C_d) profile are concerned in the cooling dominated region.

iii. Determining the capacities of DES equipment based on the predicted demand profiles. The distributed generations (DGs) in DESs are sized by maximum rectangle method (MRM). The numbers and capacities of absorption chillers and electric chillers in DESs are sized based on the peak cooling demand.

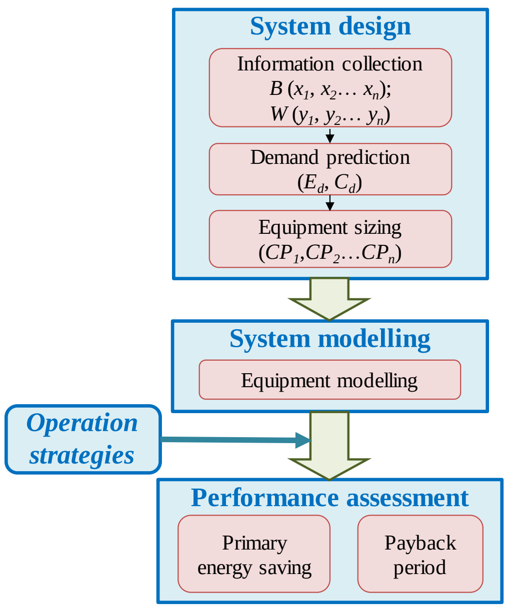

Figure 1. The performance assessment method for DESs and primary steps

2.2 *System modelling*

Models for main equipment, i.e., DGs, absorption chillers and electric chillers, are developed. In many other studies, the full load (nominal) efficiency and the practical operation efficiency, i.e. electric efficiency of DGs and coefficient of performance (COP) of chillers, are set as constant.

This is not accurate because the equipment of different capacities will have different efficiencies and their efficiencies will change under different part loads. Models in this study take the divergence of efficiency into account.

2.2.1 Models of DG

DGs generate electricity and waste heat which can be recovered at the same time. Two efficiencies, the total efficiency η_T, which is the ratio of net generated electricity plus the net recovered waste heat to net primary energy consumption, and electric efficiency η_{DG}, which is the ratio of net generated electricity to net primary energy consumption, represent the performance of DGs. Based on the given data from a major manufacturer, full load efficiencies of gas engines are plotted in Fig. 2 [17]. The functions of full load efficiencies of different DG capacities are fitted using the data in Fig. 2 and shown in Eq. 1 and 2.

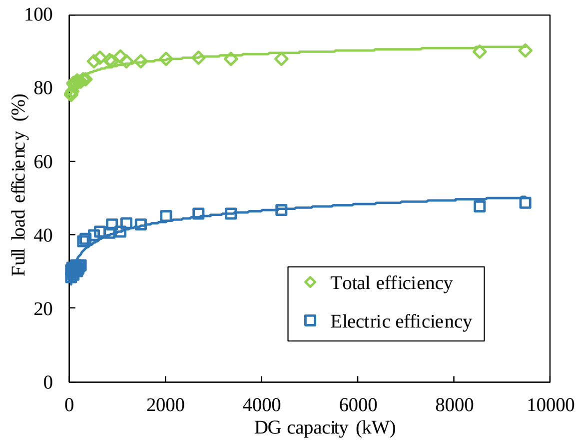

Figure 2. DGs full load efficiencies of samples

$$\eta_{T,FL} = \frac{1}{100}[2.303 \cdot \ln CP_{DG} + 70.300] \quad (1)$$

$$\eta_{DG,FL} = \frac{1}{100}[4.236 \cdot \ln CP_{DG} + 11.498] \quad (2)$$

When the generation capacity (CP_{DG}) is determined, the corresponding full load electric efficiency can be calculated by Eq. 2. Based on the accurate test study of a Capstone gas engine reported in reference [18], the DG electric efficiency reduces when the load ratio reduces, while the total efficiency keeps constant in part load conditions. Fig. 3 shows the relative electric efficiency (α_{DG}), the ratio of practical efficiency to the full load efficiency of the DG in that test, under different part loads. Eq.3 is the relative electric efficiency of DGs by fitting the data presented in Fig.3. Where r_p is the part load ratio (the ratio of practical electricity output and the rated capacity). It is assumed that all DGs in this study perform with the same relative electric efficiency. Thus, the practical electric efficiency of DGs at any part load can be estimated by Eq. 4. The primary energy consumption of the DG (F_{DG}) and centralized power plants (F_{grid}), and the amount of recovered waste heat (Q_{rc}), which can be used by absorption chillers, are estimated by Eqs. 5 to 7, respectively. η_{grid} is the electric efficiency of centralized power plants which use Combined Cycle Gas Turbine (CCGT) as generations. According to the statistical data in reference [19], this value is fixed to be 50%.

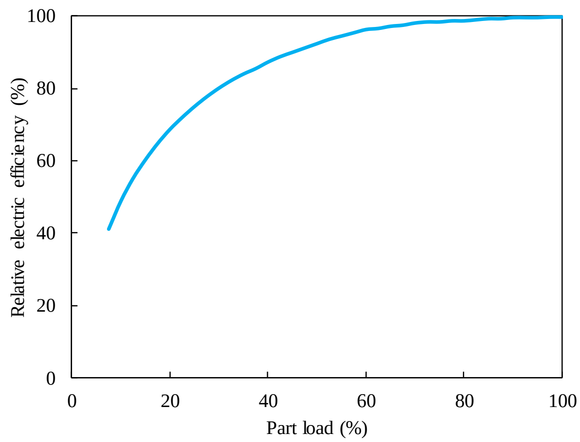

Figure 3. The relative electric efficiencies of DG at part loads

$$\alpha_{DG} = 1.334 r_p^3 - 3.208 r_p^2 + 2.605 r_p + 0.268 \quad (3)$$

$$\eta_{DG} = \alpha_{DG} \cdot \eta_{DG,FL} \quad (4)$$

$$F_{DG} = \frac{E_{DG}}{\eta_{DG}} \quad (5)$$

$$F_{grid} = \frac{E_{grid}}{\eta_{grid}} \quad (6)$$

$$Q_r = F_{DG}(\eta_{T,FL} - \eta_{DG}) \quad (7)$$

2.2.2 Models of electrical chillers and absorption chillers

In this study, centrifugal chillers are used to complement the cooling which cannot be supplied by absorption chillers. Based on the data provided by a major manufacturer, as presented in Fig. 4, the full load COP of chiller with different capacity (CP_{ec}) can be estimated by the fitting function, Eq. 8. The relative COP, which is the ratio of practical COP to full load COP, for a typical chiller under different part load ratio (r_p) presented here as an example, as shown in Fig. 5 [20, 21]. All of chillers in this study follow the same curve of relative COP, which is fitted by Eq. 9. The practical COP is the product of full load COP and relative COP as shown by Eq. 10. The electricity consumption of chillers can be estimated by Eq. 11. The absorption chillers use the recovered waste heat (Eq. 7) for cooling. The cooling output of these chillers is calculated by Eq. 12. According to reference [22], the impacts of capacities of absorption chillers and part loads on their COP can be neglected. This value is assumed to be a constant as 0.96 in this study.

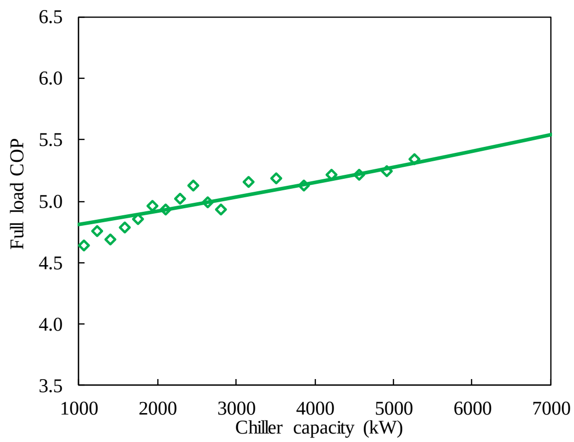

Figure 4. Chillers full load COP of different capacities

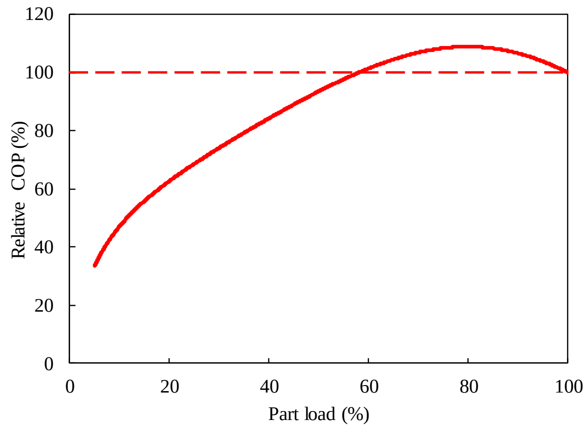

Figure 5. The relative COP of chiller at part loads

$$COP_{ec,FL} = 2.886 \times 10^{-9} CP_{ec}^2 + 0.209 \times 10^{-4} CP_{ec} + 4.711 \quad (8)$$

$$\alpha_{ec} = -0.569 r_p^3 - 0.258 r_p^2 + 1.520 r_p + 0.321 \quad (9)$$

$$COP_{ec} = \alpha_{ec} \cdot COP_{ec,FL} \quad (10)$$

$$E_{ec} = \frac{C_{ec}}{COP_{ec}} \quad (11)$$

$$C_{ac} = Q_{rc} \cdot COP_{ac} \quad (12)$$

2.3 Operation strategies

The DES operation is a complex issue because of the energy conversion and the coupling operation among the energy supply equipment and the utility grid. To ensure high efficiency of DGs during operation while satisfying various demands, an appropriate operation strategy is essential.

In DES application, two common energy policies with respect to the grid interaction are distinguished by the permission of selling the surplus electricity:

- EP_1: Selling electricity is not permitted;
- EP_2: Selling electricity to the grid is allowed if DGs produce surplus electricity.

The choice of operation strategy is governed by the energy policy. Two operation strategies, namely following hybrid load (FHL) and following thermal load (FTL), are employed to control the operation of DES.

2.3.1 FHL strategy

Fig. 6 (a) illustrates the following hybrid load (FHL) operation strategy adopted in Pol_1. The *x*-axis represents the electricity demand, and the *y*-axis shows the cooling demand. The black curve represents the outputs of absorption chillers (ACs), C_{ac}, depends on the electricity output of DGs. The left side of this line ends at a minimum output value (25% of the DG rated capacity) as DGs should not be operated beyond this limit due to its low efficiency [23]. The right side of this line ends at the maximum output or the rated capacity of DGs. The DES operating condition can be divided into four areas. The FHL strategy is presented as four cases associated to the four areas as follows.

Case 1h: $E_d \geqslant E_{max}$; $C_d \geqslant C_{max}$: Both DGs and absorption chillers operate at the maximum load. However, their outputs are not sufficient to meet the energy demands. The gap of electricity supply will be imported from the grid and the cooling will be supplied by electric chillers.

Case 2h: $E_d \geqslant E_{min}$; $C_{min} < C_d < C_{ac}$: The cooling demand is less than the cooling supplied by absorption chillers when the output of DGs match the electricity demand, as the point B_1 shows. In this case, absorption chillers operate to meet the cooling load at the point B while the DGs produce a corresponding amount of electricity. The gap of electricity supply will be imported from the grid.

Case 3h: $E_{min} < E_d < E_{max}$; $C_d \geqslant C_{ac}$: The cooling demand is larger than the cooling supplied when the output of DGs match the electricity demand, as the point A_1 shows. In this case, the DGs operate to meet the electricity load at the point A while absorption chillers produce a corresponding amount of cooling. The gap of cooling supply will be supplied by the electric chillers.

Case 4h: $E_d < E_{min}$ or $C_d < C_{min}$: DGs are off because the power demand is lower than the minimum output of DGs. The electricity is imported from the grid and the cooling is supplied by the electric chillers.

2.3.2 FTL strategy

Fig. 6 (b) illustrates the following thermal load (FTL) operation strategy which is adopted in Pol_2. The detail is presented in the following ways:

Case 1t: $C_d \geqslant C_{max}$: Both DGs and absorption chillers operate at maximum load. The gap of electricity supply will be imported from the grid if it is insufficient and the surplus of electricity generated can be sold to the grid if it is more than the power demand. The insufficient cooling will be supplied by electric chillers.

Case 2t: $C_{min} < C_d < C_{max}$: In this case, absorption chillers operate to match the cooling load while DGs produce a corresponding amount of electricity. The gap of electricity supply will be imported from the grid (from operation point B to demand point B_1) while the surplus generated electricity is be sold to the grid (from operation point A to demand point A_1).

Case 3t: $C_d < C_{min}$: DGs are off because the energy demand is lower than the minimum output. The electricity is imported from the grid and the cooling is supplied by electric chillers.

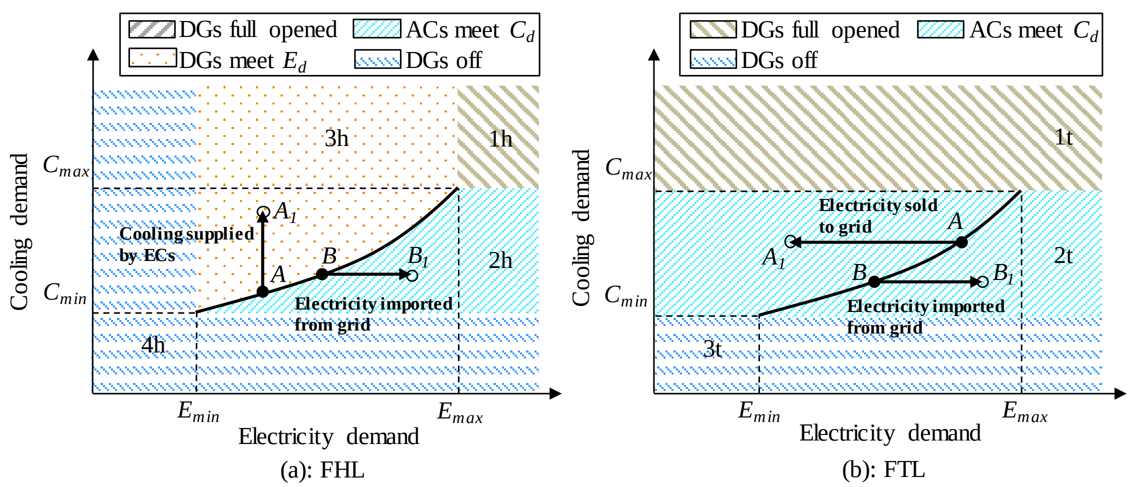

Figure 6. DES operation strategies employed in this study

2.4 Performance assessment criteria

The performance of DESs in this study is assessed using the results of system simulation. Two values, the primary energy saving and the payback period, are adopted as the main assessment criteria of energy performance and economic performance, respectively.

2.4.1 Primary energy saving (PES)

The primary energy saving (*PES*) of DES is regarded as the energy saving of DES in this study when compared with the centralized energy system (CES). It is the ratio of annual energy saving and the annual energy consumption of CES, as shown in Eq. 13. Where F_{DES} is the primary energy consumption of DES as shown in Eq. 14. F_{CES} is the corresponding CES consumption for generating the same amounts of electricity and cooling as shown in Eq. 15. *i* and *k* are the number of day and hour, respectively. A higher value of primary energy saving denotes better energy performance of a DES.

$$PES = \frac{F_{CES} - F_{DES}}{F_{CES}} \times 100\% \tag{13}$$

$$F_{DES} = \sum_{i=1}^{365} \sum_{k=1}^{24} \left(F_{ik,DG} + F_{ik,grid} \right) \tag{14}$$

$$F_{CES} = \sum_{i=1}^{365} \sum_{k=1}^{24} \frac{1}{\eta_{grid}} (E_{ik,d} + E_{ik,sell} + \frac{C_{ik,d}}{COP_{ik,ec}}) \tag{15}$$

2.4.2 Payback period (PBP)

The payback period (*PBP*) indicates number of years needed for the payback of the surplus capital cost if using DES to replace CES. Thus, the shorter payback period indicates better economic performance of the DES. This value is the ratio of capital cost difference and operating cost difference as shown in Eq. 16. Where ΔCc and ΔOc are the increase of system capital cost and the annual operation cost saving shown in Eqs. 17 and 18, respectively. Cc_{eq} is the equipment capital cost. n_1 and n_2 are the equipment number for the DES and the CES. The first part of right side in Eq. 18 is the annual operation cost of CES, and the second part is the DES which includes the energy cost and the maintenance cost. $Cost_e$ is the price of electricity (USD/kWh). $Cost_f$ is the price of fuel, i.e., natural gas, USD/kWh (i.e. price per kWh higher heating value). $Cost_{e,sell}$ is the feed-in tariff. CM_{DG} is the maintenance cost coefficient, which is the maintenance cost of DGs associated with each unit (kWh) of electricity generation. The details of the facility prices are shown in Table 1.

$$PBP = \frac{\Delta Cc}{\Delta Oc} \tag{16}$$

$$\Delta Cc = \sum_{m=1}^{n_1} CP_m \cdot Cc_{m,eq} - \sum_{n=1}^{n_2} CP_n \cdot Cc_{n,eq} \tag{17}$$

$$\Delta Oc = \sum_{i=1}^{365} \sum_{k=1}^{24} \left\{ \left(E_{ik,d} + \frac{C_{ik,d}}{COP_{ik,ec}} \right) \cdot Cost_e - \left[\left(E_{ik,grid} \cdot Cost_e + F_{ik,DG} \cdot Cost_f - E_{ik,sell} \cdot Cost_{e,sell} \right) + CM_{DG} \cdot E_{ik,DG} \right] \right\} \tag{18}$$

Table 1. Prices of the facility used in this study [16]

Facility	DGs	Absorption chillers	Electric chillers	Maintenance
Price (USD/kW)	$3711.78 - 280.47\ln(CP_{DG})$	$369.50 - 36.78\ln(CP_{ac})$	150.45	$0.0394 - 0.0031\ln(CP_{DG})$

3 Organization of case studies and energy pricing in Hong Kong

To study the feasibility of DESs in Hong Kong, energy demands of buildings are predicted for the system design. A common design method is adopted to size equipment capacities based on the energy demands. Local energy prices, including electricity price and gas price, are adopted to evaluate the economic performance of DESs.

3.1 Building scale and functions

Five public buildings with different functions, including commercial building, the office building, the school, the hotel and the hospital, are chosen for analysis and comparison. Several available software, such as EnergyPlus, DesT and TRNSYS, are commonly used for buildings energy demand prediction. TRNSYS is a user friendly simulation program with better flexibility in including energy systems on simulation [24, 25]. With the building information (working schedule and physical parameters) and outdoor weather parameters (TMY data of Hong Kong), the hourly cooling demand (C_d) can be predicted using TRNSYS building model, Type 56, in this study. The electricity demand of each building includes the demand of building (E_{bldg}) and the demand of the auxiliary equipment of HVAC system (E_p), such as the pumps, the cooling towers, and the fans. The E_{bldg} can be calculated according to the guidelines on building energy codes published by the Hong Kong government [26]. The E_p can be predicted by a simplified method which is explained in the reference [27]. Assumptions made in energy demands prediction are listed below:

- A commercial building is selected when analyzing the impacts of building scale on DES performance. Its floor area changes within a range between 2,000 and 250,000 m^2.
- All the buildings are assumed to have a floor area of 60,000 m^2 when analyzing the DES performance in different buildings.
- For an individual building, the electricity demand of auxiliary equipment of HVAC system (E_p) in the CES and the DES are the same.

3.2 DES configuration and sizing

A building integrated DES, including distributed generations (DGs), chillers (absorption chillers and electric chillers) and the utility grid, is proposed to satisfy the energy demands of the building in the cooling dominated region. In the energy system, a gas engine DG produces electricity and exhausts waste heat as flue gas around 600℃ simultaneously. A mixed-effect absorption chiller, which consists of a double effect (DE) absorption chiller and a single effect (SE) absorption chiller, uses the flue gas for thermal activated cooling generation directly [22]. When the energy demand cannot be satisfied by the DG or/and the absorption chiller, the utility grid or electric chillers are used to meet the electricity and cooling demands. In the CES, the electric chillers are used to meet the cooling demand and all the electricity consumed by the building and electric chillers is supplied by the utility grid. The configurations of the DES and the CES are shown and compared in Fig. 7.

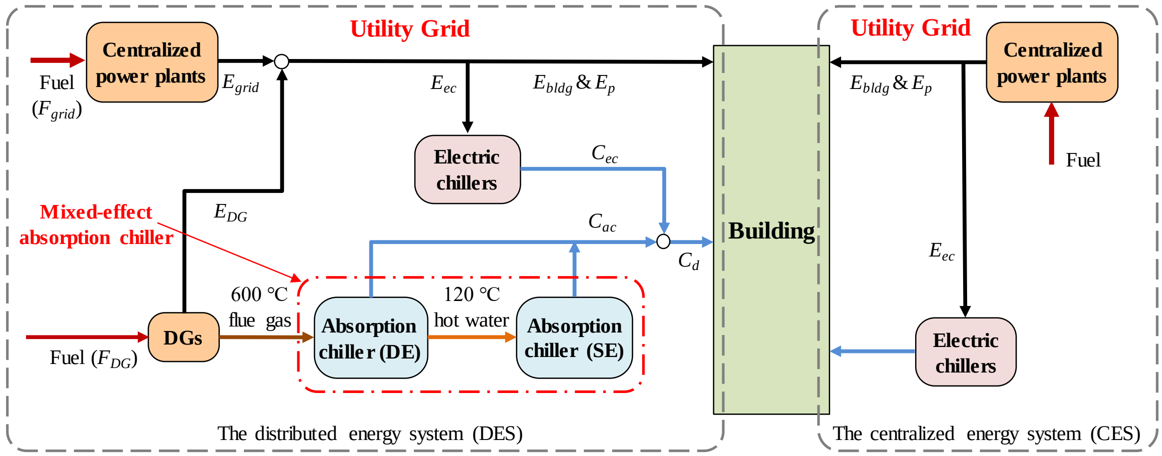

Figure 7. Configurations and energy flows of DES and CES for a building

This study uses a common design method, named maximum rectangle method (MRM), to determine the equipment capacities in DES. This method is based on the electricity demand as described in reference [28]. Fig. 8 illustrates the process of this method. A rectangle can be drawn under the cumulative curve of annual electricity demand limited to the time and the demand axis. The demand, i.e. the value at the *x*-axis, associated with the intersection of the rectangle with the maximum area determines the DG capacity.

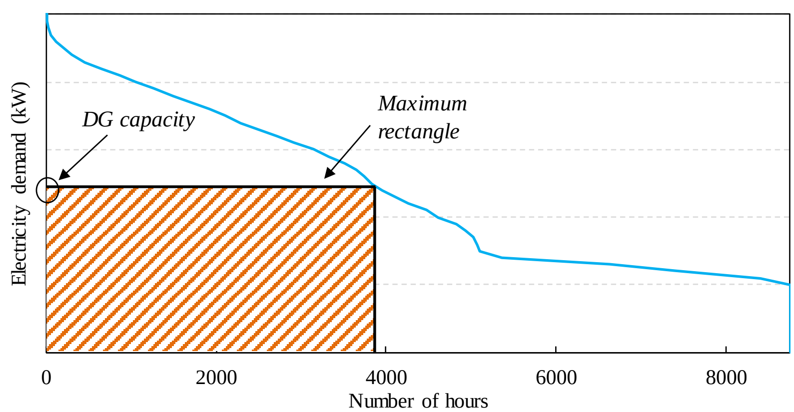

Figure 8. Cumulative curve and the application of MRM

After the DG capacity is determined, the absorption and electric chillers can be sized. The absorption chillers have the capacity to use the recovered waste heat when the DGs are operating at full load, and the capacity of electric chillers is then chosen to fill the gap of absorption chillers in satisfying the cooling demand at the design load condition, as shown in Eqs. 19 and 20. Where

N_{DG}, N_{ac} and N_{ec} are the number of DGs, absorption chillers and electric chillers, respectively. $C_{d,peak}$ is the annual peak cooling demand. The capacity of electric chillers in buildings in the CES can also be determined by Eq. 20, while both N_{ac} and CP_{ac} are zero.

In this study, the DG capacity is selected within a range between 50 and 8500 kW with an interval of 50 kW. The absorption chiller capacity ranges from 100 to 2500 kW and the electric chiller capacity ranges from 100 to 7500 kW.

$$CP_{ac} = CP_{DG} \frac{(\eta_{T,FL} - \eta_{DG,FL})}{\eta_{DG,FL}} COP_{ac} \cdot \frac{N_{DG}}{N_{ac}} \tag{19}$$

$$CP_{ec} = \frac{C_{d,peak} - N_{ac} CP_{ac}}{N_{ec}} \tag{20}$$

3.3 Energy pricing and its deduction

Hong Kong government intends to replace current coal-fired power plants by natural gas generations [29, 30]. Thus, the current electricity price cannot be used directly for the economic assessment and an appropriate grid electricity price need to be deduced. The current electricity price in Hong Kong consists of the total energy cost and the other cost ($Cost_{other}$) [31]. In this study, the other cost, which is assumed to be an independent value, is deduced by subtracting the total energy cost from the electricity price. According to the tariff data of China Light and Power Company (CLP), the major utility company in Hong Kong [32, 33], the other cost is estimated to be 0.0781 USD/kWh. When natural gas is used as the fuel, the grid electricity price equals the sum of the natural gas cost and the other cost as shown in Eq. 21. There are three different natural gas prices used in this study. One (Gas price I) is the price of natural gas which is directly purchased by CLP from international energy market [33]. The second (Gas price II) is the current natural gas price [34] given by the local supplier in Guangzhou near Hong Kong, which is a metropolis in Mainland China. The third (Gas price III) is the current natural gas price [35] given by the local supplier in Hong Kong. In the DES, the feed-in tariff, or the selling price of electricity, is assumed to be 80% of the grid electricity price as shown in Eq. 22. Table 2 summarizes the gas and electricity prices used in this study.

$$Cost_e = Cost_{other} + Cost_f \cdot \frac{1}{\eta_{grid}} \tag{21}$$

$$Cost_{e,sell} = 0.8 \cdot Cost_e \tag{22}$$

Table 2. The list of gas and electricity prices

Gas price (USD/kWh)		Grid electricity price (USD/kWh)	Feed-in tariff (USD/kWh)
Gas price I	0.0571		
Gas price II	0.0722	0.1923	0.1538
Gas price III	0.1075		

4 Results and analysis

For the application of DESs in Hong Kong, it is assumed that the natural gas is purchased at Gas price I in the market, and the generated electricity cannot be selling to the grid, i.e., EP_1 is adopted. The impacts of major design parameters on the performance of DESs are presented in this section. With respect to the grid interaction, EP_2, i.e., selling generated electricity is permitted, is adopted and the impacts of this energy policy are investigated. Based on the test results, the economic benefits of DESs under different natural gas prices are compared and discussed. A government incentive is introduced and its improvement on the DES performance is analyzed.

4.1 Impacts of building scale and function

When selling generated electricity is not permitted, i.e. energy policy EP_1 is adopted, the system follows the FHL operation strategy. The buildings with different scales and functions result in different energy demands. Thus, impacts of these factors on the performance of the building integrated DES are significant. For commercial buildings with different scales, capacities and the number of equipment are presented in Table 3. It can be seen that DGs and chillers, applied in large-scale buildings, have larger capacities with higher efficiencies, both total efficiency $\eta_{T,FL}$ and electric efficiency $\eta_{DG,FL}$. The annual primary energy savings of DESs in buildings of different scales are shown in Fig. 9. A positive value denotes that the DES saves primary energy compared with the corresponding CES, while the negative denotes that the DES consumes more than the

CES. In small-scale buildings (i.e., the floor area is less than 40,000 m^2), the ratio is negative. It decreases when the building scale decreases. This indicates that the DES is inapplicable in small-scale buildings because the DES consumes more primary energy than the CES. The saving increases when the building scale increases. It reaches 6.15% when the scale is 100,000 m^2. However, this value is saturated at 6.43%, indicating that the DES cannot achieve very significant energy saving in this cooling dominated region when selling electricity is not permitted.

Table 3. Detailed equipment selection for the building energy systems

Building scale (m^2)	DES								CES	
	DG (kW)	$\eta_{DG,FL}$ (%)	$\eta_{T,FL}$ (%)	N_{DG}	Absorption chiller (kW)	N_{ac}	Electric chiller (kW)	N_{ec}	Electric chiller (kW)	N_{ec}
2,000	100	30.56	80.60	1	140	1	120	3	130	4
5,000	250	34.35	82.71	1	300	1	280	3	280	4
10,000	450	37.28	85.53	1	535	1	620	3	600	4
20,000	850	40.17	85.53	1	950	1	1270	3	1200	4
40,000	1750	43.11	87.19	1	1720	1	2600	3	2380	4
60,000	2550	44.69	88.06	1	2370	1	3970	3	3570	4
100,000	4550	47.16	89.39	1	1310	2	6610	3	5940	4
250,000	5400	47.90	89.78	2	1525	3	6290	8	5940	10

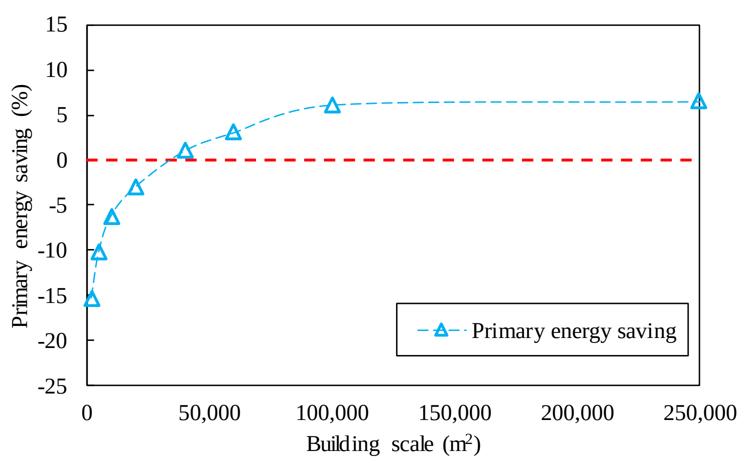

Figure 9. Performance of DESs *vs* building scale when selling electricity is not permitted

Fig. 10 presents the DES energy performance of different functions of buildings. Due to the difference of building functions and working schedules, the annual primary energy consumptions of buildings are different. For example, the primary energy consumed by the commercial building is 58298 MWh in a year and it is about half for the school (28567 MWh). This is because the commercial building has significantly higher energy demands during the nighttime and weekends compared with the school building. Compared with the CES, the ranking order of the DES in terms of primary energy saving is: the commercial building (3.07%), the office building (2.98%), the hotel (2.49%), the hospital (2.06%) and the school (1.43%). This case indicates that the building integrated DES is not practically beneficial to all buildings in term of energy saving.

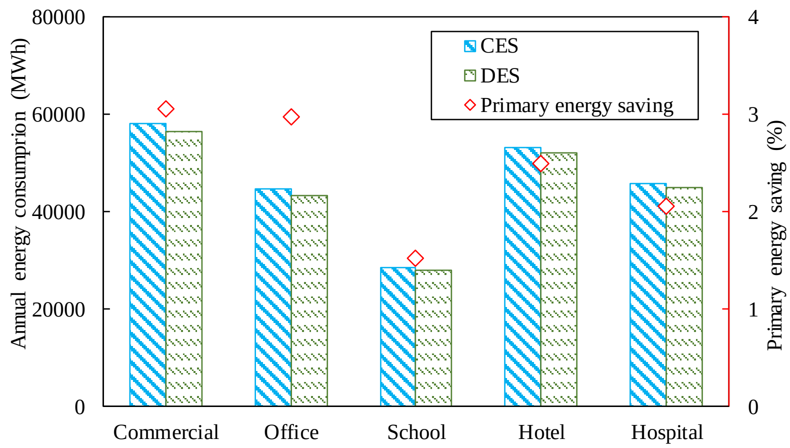

Figure 10. Performance of DESs in buildings of different functions when selling electricity is not permitted

4.2 Impacts of equipment capacities

According to the test results, capacities of the DESs affect the system energy production and the energy consumption. A hypothetic commercial building of 100,000 m^2 floor area is regarded as the case building. The DG capacity varies from 2000 kW to 8000 kW, and capacities of chillers vary consequently according to Eqs 19 and 20. Compared with the CES, the primary energy saving of the DES with various DG capacities, when selling electricity is not permitted, is shown as Fig. 11. It can be seen that, when the DG capacity increases, the system energy saving increases because of the raise of equipment efficiency. The saving reaches the maximum value, 6.54%, when the DG capacity is 5350 kW, and reduces when the capacity continues to increase. This is because the oversized DG will operate under part loads with relatively lower efficiency. Therefore, the primary energy consumption of the DES increases so that the system energy performance decreases.

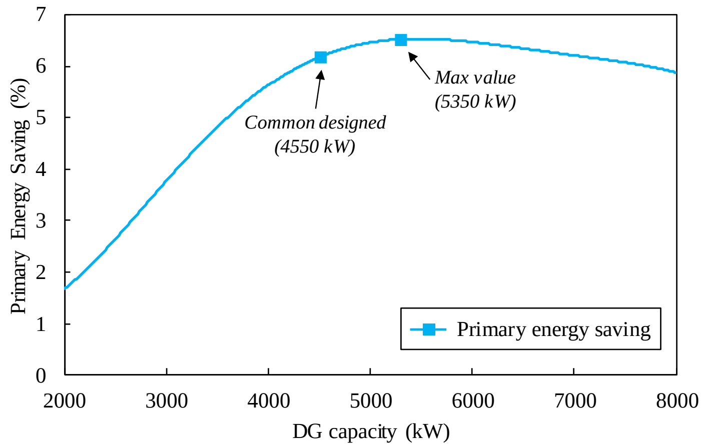

Figure 11. Energy performance of DESs of variable DG capacities when selling electricity is not permitted

Fig. 12 illustrates the system payback period with different DG capacities in the same case. The results indicate that the system payback period remains a relative high value when the DG capacity is either undersized or oversized. When a DG of small capacity is adopted, the operation cost cannot be reduced apparently. Thus, the additional capital cost of DES cannot be recovered within a short time. When the DG is oversized, the capital cost increases but the operation cost will not reduce, or only reduce slightly. Thus, the payback period increases. For this building, the minimum payback period is 1.98 years when the DG capacity is 4100 kW. Meanwhile, the marked points in Fig. 11 and Fig. 12 indicate that the DES based on common design cannot realize the potential of energy saving or achieve the maximum economic performance.

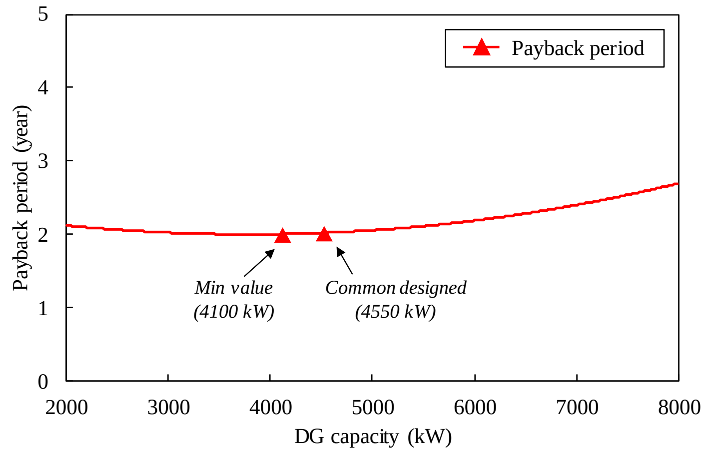

Figure 12. Economic performance of DES with variable DG capacities when selling electricity is not permitted

4.3 Impacts of grid interaction policy

When selling generated electricity is permitted, i.e. energy policy EP_2 is adopted, the system follows the FTL operation strategy. Fig. 13 and Fig. 14 present the comparison of DES energy saving and the annual electricity generation respectively, under two different grid interaction policies. When the surplus electricity can be sold to the grid, the primary energy saving increases significantly and this increase becomes larger when the DG capacity increases. For example, the primary energy saving increases by 1.59% (from 5.73% to 7.32%) when the DG capacity is 4000 kW, and increases by 7.67% (from 5.88% to 13.55%) when the DG capacity increases to 8000 kW. From Fig. 14 we can see that annual electricity generation of DESs increases in EP_2. It indicates that: 1) the practical electric efficiency of DGs increases while less primary energy will be consumed; 2) more recovered heat can be used for cooling due to the increase of DG production. Thus, the electricity consumption of electric chillers in the DES reduces.

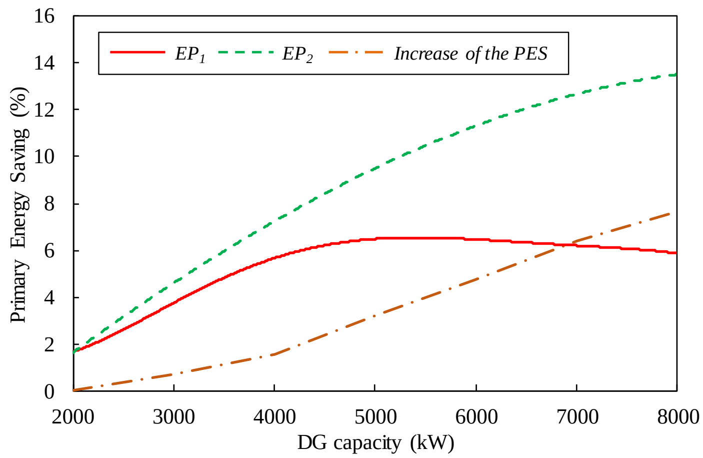

Figure 13. Energy performance of DESs under different grid interaction policies

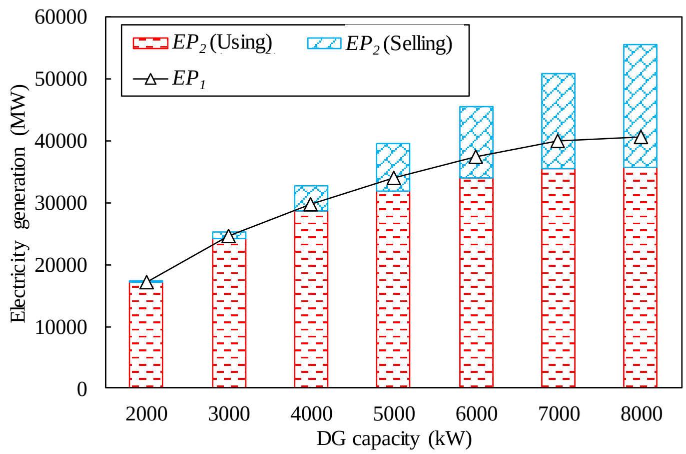

Figure 14. Annual electricity generations of DESs under different grid interaction policies

Fig. 15 shows that the payback period decreases due to the use of energy policy EP_2. By selling the generated electricity with an appropriate feed-in tariff, the DES can reduce its operation cost according to Eq. 18. This reduces the payback period and improves the system economic performance. When the DG capacity is 4000 kW, for instance, the payback period reduces by 0.14 years (from 1.99 years to 1.85 years). This reduction is enlarged with the increase of the DG capacity, and reaches 0.75 year when the DG capacity is 8000 kW (from 2.71 years to 1.96 years). In cooling dominated regions, the building integrated DES can achieve higher energy and economic performance when selling electricity of DES is permitted.

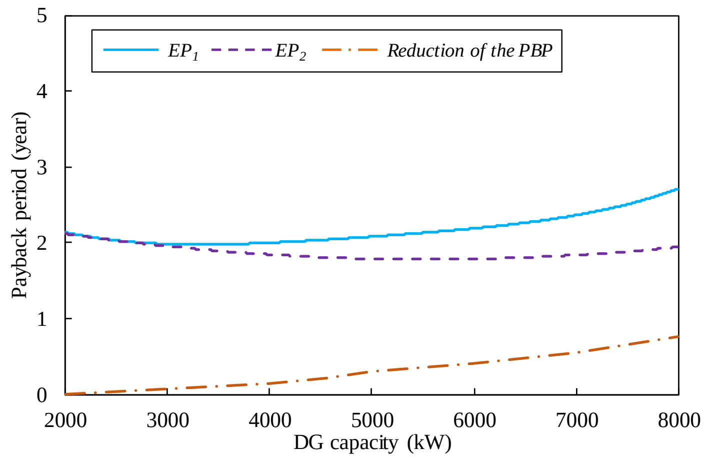

Figure 15. Economic performance of DESs under different grid interaction policies

4.4 Impacts of gas price

The natural gas price in the market can affect the operation cost of DES. Three natural gas prices, which are introduced in section 3.3, are adopted to analyze such impacts. Comparing the operation cost of DESs and CESs, the operation cost saving can be estimated by Eq. 18. Fig. 16 shows the cost savings when different gas prices are adopted. The positive value denotes that the system operation cost reduces due to the application of DES. The DES achieves economic benefits and the surplus capital cost of the DES can be recovered. While the negative value denotes that the system operation cost increases. Thus, the DES losses the economic benefits and the surplus capital cost cannot be recovered. When Gas price I is adopted, the operation cost saving of the system is larger than the case when Gas price II is adopted. This indicates that the DES can achieves economic advantages in both situations and the cost benefit is improved in the first situation (i.e., Gas price I is adopted). When Gas price III (i.e., the current gas price in Hong Kong) is used, the operation cost saving is negative, indicating that the use of DES increases the building energy system operation cost. The application of DESs is limited in this situation because both the capital cost and the operation cost increase.

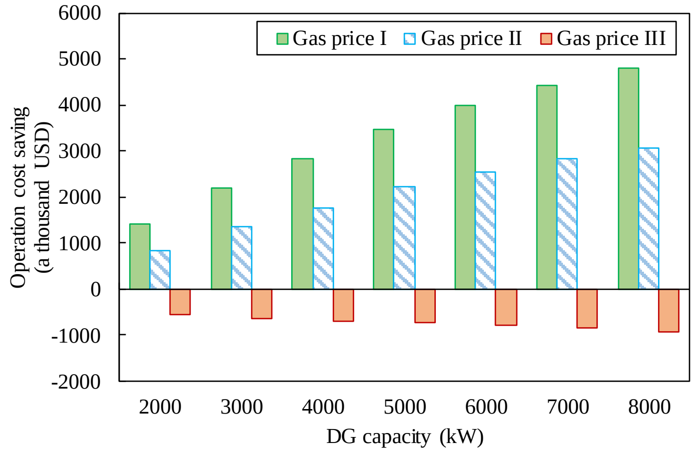

Figure 16. The operation cost savings under different gas prices

4.5 *Impacts of government incentives*

To encourage to reduce the energy consumption, government may provide some financial support as economic incentives to the DES investors according to primary energy saving [36]. In this paper, the impacts of this incentive on the performance of local DESs are investigated.

4.5.1 *Government incentive*

It is assumed that the economic incentive, which is given by government, is proportional to the primary energy saving of the DES. The adjusted operation cost, which can be calculated by Eq. 23, equals to the sum of system energy cost and the maintenance cost, subtracted by the energy saving incentive. In Eq. 23, *PS* is the incentive coefficient of energy saving. It is the amount of money which the government intends to subsidize for each unit of primary energy saving. In this study, the incentive coefficient is chosen as 0.0285 USD/kWh, i.e., 50% of the fuel price.

$$Oc = \sum_{i=1}^{365}\sum_{k=1}^{24}\left[\left(E_{ik,grid}\cdot Cost_e + F_{ik,DG}\cdot Cost_f - E_{ik,sell}\cdot Cost_{e,sell}\right) + CM_{DG}\cdot E_{ik,DG} - (F_{CES,ik} - F_{DES,ik})\cdot PS\right] \tag{23}$$

4.5.2 *Analysis of the impacts*

The commercial building introduced in 4.2 is regarded as the case building. EP_2 is adopted and the DES can sell the generated electricity to the grid. Fig. 17 presents the system payback period of two cases: EP_2 and EP_2 with government incentive. It can be seen that the payback period reduces when government subsidize for the primary energy saving. The surplus capital cost of the DES can be recovered within 2 years when the DG capacity varies from 2000 kW to 8000 kW. It is because that the incentive for energy saving results in the reduction of the system operation cost, so that the payback period is reduced consequently. Another impact is the improvement of economic performance of the DES with larger DGs. When the largest DG (8000 kW) is adopted, the payback period reduces to 1.67 years, which corresponds closely to the minimum value, 1.64 years. This indicates that the government incentive is an effective policy to improve the benefits of DESs in cooling dominated regions.

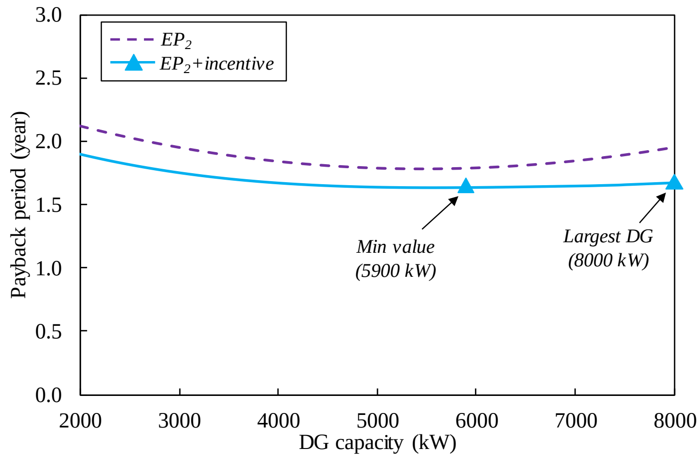

Figure 17. Impact of government incentive on the payback period

5 Conclusions

Building integrated distributed energy systems (DESs) in a cooling dominated region are studied, and their performance is quantified and assessed using different evaluation criteria. The impacts of major design parameters and energy policies on the performance of DESs are investigated. The building integrated DESs can achieve substantial benefits (i.e., up to 13.55% of primary energy saving and 1.64 years of payback period) in this region under certain situations, while the scale and function of buildings, the design capacity of DES as well as the energy policy and gas price have significant impacts on the practical benefits of DESs. Based on test results, some detailed conclusions can be drawn as follows:

- The scale of building affects the benefit of using DESs significantly. The use of DESs is found to be beneficial only when a building scale is larger than 40,000 square meters. Even when selling electricity is not permitted, DESs can save up to 6.43% of annual primary energy consumption.
- The function of buildings also has obvious impacts on the benefits of using DESs. It is found that the use of DESs in the commercial building has more benefit. It is less for office buildings and it is the least for public buildings like schools.
- For a given building, both undersized and oversized DGs will result in reduced DES performance. With proper design, the use of DES can achieve 6.54% primary energy saving and 1.98 years of payback period when selling electricity is not permitted.
- Permission for selling electricity to the grid can improve the benefits of using DES effectively. The primary energy saving of using DESs can be increased by 7.01% (from 6.54% to 13.55%) when selling electricity is permitted.
- Reasonably low gas price is a prerequisite for cost-effective operation and application of DESs. The current gas price in Hong Kong consumer market cannot allow cost-effective application while the current price of gas purchased from the international market allow rather cost-effective application of DESs.

Acknowledgements

The research presented in this paper is financially supported by a grant (152694/16E) of the Research Grant Council (RGC) of the Hong Kong SAR and a grant under the Strategic Focus Area (SFA) Scheme of the Research Institute for Sustainable Urban Development (RISUD).

Nomenclatures

Abbreviations

CES	centralized energy system
DES	distributed energy system

DG	distributed generation
PBP	payback period
PES	primary energy saving

Symbols

C	cooling
Cc	capital cost
CM	maintenance cost coefficient
Cost	energy price
CP	capacity
E	electricity
F	primary energy
N	number of equipment
Oc	operation cost
PS	incentive coefficient
Q	thermal power
r	ratio

Greek symbols

α	relative efficiency
η	efficiency

Subscripts

ac	absorption chiller
d	demand
e	electricity
ec	electric chiller
eq	equipment
f	fuel
FL	full load

grid	the utility grid
p	part load
rc	recovered waste heat
T	total

References

[1] M. F. Akorede, H. Hizam, E. Pouresmaeil, Distributed energy resources and benefits to the environment, Renewable and Sustainable Energy Reviews 14 (2010) 724-734.

[2] Haikarainen. C, Pettersson. F, Saxén H, A model for structural and operational optimization of distributed energy systems. Applied Thermal Engineering 70 (2014) 211-218.

[3] K. Alanne, A. Saari, Distributed energy generation and sustainable development, Renewable and Sustainable Energy Reviews 10 (2006) 539-558.

[4] Q. H. Chen, W. L. Wang, J. F. Lu, et al., An overview of the political, technical and economical aspects of gas-fired distributed energy system in China. Applied Thermal Engineering 52 (2013) 531-537.

[5] W. S. Tan, M. Y. Hassan, M. S. Majid, et al., Optimal distributed renewable generation planning: A review of different approaches, Renewable and Sustainable Energy Reviews 18 (2013) 626-645.

[6] G. Pepermans, J. Driesen, D. Haeseldonckx, et al., Distributed generation: definition, benefits and issues, Energy Policy 33 (2005) 787-798.

[7] H. Cho, A. D. Smith, P. Mago, Combined cooling, heating and power: A review of performance improvement and optimization, Applied Energy, 136 (2014) 168-185.

[8] W. Gu, Z. Wu, R. Bo, et al., Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review, International Journal of Electrical Power & Energy Systems 54 (2014) 26-37.

[9] N. Fumo, P. J. Mago, L. M. Chamra, Analysis of cooling, heating, and power systems based on site energy consumption, Applied Energy 86 (2009) 928-932.

[10] P. J. Mago, A. K. Hueffed, Evaluation of a turbine driven CCHP system for large office buildings under different operating strategies, Energy and Buildings 42 (2010) 1628-1636.

[11] Q. Wu, H. B. Ren, W. J. Gao, et al., Multi-criteria assessment of combined cooling, heating and power systems located in different regions in Japan. Applied Thermal Engineering 73 (2014) 660-670.

[12] H. Cho, P. J. Mago, R. Luck, et al., Evaluation of CCHP systems performance based on operational cost, primary energy consumption, and carbon dioxide emission by utilizing an optimal operation scheme, Applied Energy 86 (2009) 2540-2549.

[13] M. Li, X. Z. Jiang, D. Zheng, et al., Thermodynamic boundaries of energy saving in conventional CCHP (Combined Cooling, Heating and Power) systems, Energy 94 (2016) 243-249.

[14] G. Allan, I. Eromenko, M. Gilmartin, et al., The economics of distributed energy generation: A literature review, Renewable and Sustainable Energy Reviews 42 (2015) 543-556.

[15] R R. Bush, D. A. Jacques, K. Scott, et al., The carbon payback of micro-generation: An integrated hybrid input–output approach, Applied Energy 119 (2014) 85-98.

[16] C. Y. Zheng, J. Y. Wu, X. Q. Zhai, et al., Impacts of feed-in tariff policies on design and performance of CCHP system in different climate zones, Applied Energy 175 (2016) 168-179.

[17] GE Jenbacher gas engine, Available: https://powergen.gepower.com/products/reciprocating-engines.html

[18] Capstone Turbine Corporation, Available: https://www.capstoneturbine.com

[19] Eurelectric and V. PowerTech, Efficiency in electricity generation 2003.

[20] W. J. Gang, S. W. Wang, G. Augenbroe, et al., Robust optimal design of district cooling systems and the impacts of uncertainty and reliability, Energy and Buildings 122 (2016) 11-22.

[21] C. C. Yan, W. X. Shi, X. T. Li, Y. Zhao, Optimal design and application of a compound cold storage system combining seasonal ice storage and chilled water storage. Applied Energy 171 (2016) 1-11.

[22] J. Wang, J. Wu, Investigation of a mixed effect absorption chiller powered by jacket water and exhaust gas waste heat of internal combustion engine, International Journal of Refrigeration 50 (2015) 193-206.

[23] L. M. Chamra, P. J. Mago, N. Fumo, Cooling, heating, and power energy performance for system feasibility, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 222 (2008) 347-354.

[24] TRNSYS-Transient System Simulation Tool. Available: http://www.trnsys.com

[25] S. W. Wang, R. Tang, Supply-based feedback control strategy of air-conditioning systems for direct load control of buildings responding to urgent requests of smart grids, Applied Energy 201 (2017) 419-432.

[26] EMSD, Hong Kong, Guidelines on Performance-based Building Energy Code, 2007.

[27] X. Q. Kong, R. Z. Wang, X. H. Huang. Energy optimization model for a CCHP systemwith available gas turbines. Applied Thermal Engineering 25 (2005) 377–391.

[28] S. Sanaye, N. Khakpaay, Simultaneous use of MRM (maximum rectangle method) and optimization methods in determining nominal capacity of gas engines in CCHP (combined cooling, heating and power) systems, Energy 72 (2014) 145-158.

[29] CLP Hong Kong, CLP Information Kit, Available: https://www.clp.com.hk/en/about-clp-site/corporate-information-site/scheme-of-control-site/Documents/4.1%20CLP%20Information%20Kit.pdf

[30] K. F. Fong, C. K. Lee, Performance analysis of internal-combustion-engine primed trigeneration systems for use in high-rise office buildings in Hong Kong, Applied Energy 160 (2015) 793-801.

[31] CLP Hong Kong, CLP Tariff Component, Available: https://www.clp.com.hk/en/

[32] CLP Hong Kong, 2015 Tariff Review Presentation, 2015.

[33] CLP Hong Kong, 2015 Energy Costs Breakdown, 2015.

[34] Guangzhou Municipal Development and Reform Commision, Standard of Natural Gas Price in Guangzhou, Available: http://www.gzplan.gov.cn/

[35] Gas tariff in Hong Kong, Available: https://www.towngas.com/eng/cust/household/custservice/tariff.aspx

[36] R. Dong, J. Xu, Impact of differentiated local subsidy policies on the development of distributed energy system, Energy and Buildings 101 (2015) 45-53.