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A Holistic Supply and Demand Co-optimization for Distributed Energy System

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ABSTRACT

The distributed energy system is considered to be introduced in urban area, which proposes a new effective approach to improve the efficiency of energy system and the sustainability of urban. The present study proposes an integrated approach for optimal design of distributed energy system considering the optimization of supply side and demand side simultaneously. On the demand side, a scenario tree is established to quantify the energy saving technology including envelop upgrades of window, wall, roof. On the supply side, another scenario tree is developed to describe the variation of solar radiation, typical days, and typical seasons. Moreover, a MILP model is built to optimize the economic performance taking carbon tax into account. The results indicate that the combination of optimal selection of energy saving technology and optimal design of energy conversion technology enables the DES model to improve the economic performance, especially considering the carbon tax. Moreover, the optimal system configuration and dispatch strategy become more reasonable and flexible by introducing the demand side technology into DES planning model.

Keywords: Distributed energy system, Programming model, Co-optimization of supply and demand, Carbon tax.

1. INTRODUCTION

Distributed energy system (DES), integrating multiple energy flows in one system, is considered as an effective approach to improve the sustainability of urban energy system and deal with the environmental issues, since it has lower carbon emission and utilizes local renewable energy resources. The urban buildings and construction sector accounts for nearly half of energy use and carbon emissions simultaneously.

Previous studies always focus on the optimization for the system configuration of supply-side design rather than optimizing the supply side and demand side simultaneously. Researchers consider them as two different issues needed to be addressed twice. Diakaki et al. [1] presented an optimization model for optimal design of building energy system with energy saving research. Jing et al. [2] and Zhang et al. [3] improved the optimization model of energy system to the multi-objective optimization model considering economic and environmental objectives. Moreover, Nielsen at al. [4] proposed a technology-selection model for designer to choose the optimal energy saving measure based on the heating supply design. Jennings et al. [5] presented a detailed planning model for urban energy system considering supply side and demand side to identify the feasibility of simultaneous optimization. Zheng et al. [6] conducted an optimization model combining industrial retrofitting method and supply side design, whose results shows that the grid electricity price is the essential for system configuration of energy system.

In addition, other studies concentrated on the multi-objective optimization for energy system on supply-side design considering various objectives. Gonçalves et al. [7] developed an automated home energy management system for allocating demand-side resources and optimal design considering thermal comfort and cost objectives. Terlouw et al. [8] proposed a multi-objective mixed integer linear programming model to select the storage technology for energy system based on the optimal solution of capacity cost and carbon emissions. Cui et al. [9] and Pesaran et al. [10] conducted comprehensive reviews on the selection of objectives and optimization methods for urban energy system. Jing et al. [11]

highlighted the importance of posteriori decision-making for identifying a compromising final solution. Generally, most of the studies optimize the urban energy system considering supply-side design rather than simultaneous optimization of supply-side and demand-side design due to the complexity and computational cost.

According to the review of previous research, the distributed energy system is always modeled on the supply side, while the optimization of demand side is neglected. Hence, this study proposes an integrated optimization model of DES combing the optimal design of supply side and the optimal selection of energy saving technologies for demand side. The building performance simulation is conducted to obtain the whole-year energy demands including heating, cooling, and electrical demands. Meanwhile, a scenario tree structure is developed to describe various energy saving technologies for the retrofitting of building envelops, in which the nodes indicate various scenarios with different construction cost and energy demands. For the optimization of supply side, a mixed integer linear programming (MILP) is established to optimize the system configuration and dispatch strategy for a CCHP based distributed energy system, in which another scenario tree structure is developed to describe the variation of solar radiation, seasons, and typical days. Moreover, the various levels of carbon tax are introduced to quantify the effect of energy-saving and considered as a part of operation cost. Finally, the energy-saving technologies, optimal system configuration, and dispatch strategy is achieved and analyzed, respectively.

2. METHODOLOGY

2.1 Framework and model development

The roadmap and methods are illustrated in Fig. 1, which combines the optimal design of supply side and the optimal selection of demand side. A technology-rich model for optimal design of community-level DES is developed. The DES model includes CHP, PV panel, electrical chiller, heat pump, storage tank, gas boiler, bulk grid, and battery, which have been integrated to meet the demand of district buildings.

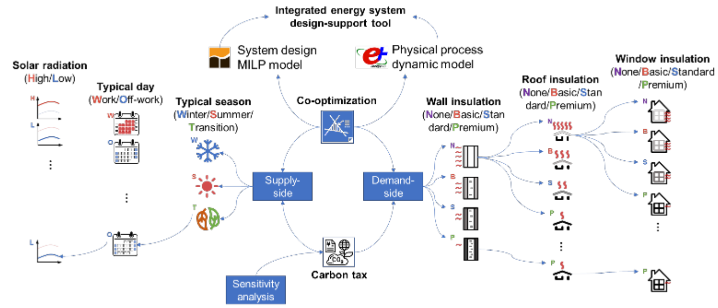


Fig.1 Roadmap of the proposed approach.

As shown in Fig. 2, within each building, a subsystem is implemented potentially incorporating a range of energy-supply technologies and demand-side energy saving measures. Energy transfers between buildings and interactions with the utility grid are also considered. The optimization model would select a subset of these supply technologies and a scenario of energy-saving technologies, while the installed capacity, network, dispatch strategy are optimized in terms of the economic objective.

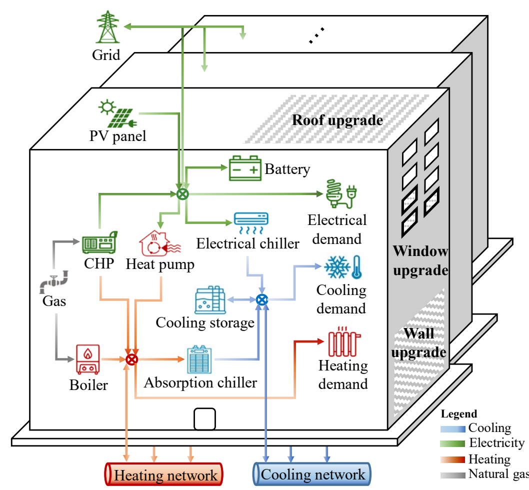


Fig.2 Superstructure of the proposed DES.

2.2 Objective functions

The economic and environmental indices selected in the proposed study should reflect the comprehensive performance in the life cycle of DES system. The environmental index, the reduction of carbon emission, can be replaced by the carbon tax which can be integrated with the economic index, total annual cost. The objective index includes capital cost, additional cost of energy-saving technologies, operation cost and benefit of carbon emission reduction.

$$TAC = CAPEX + \sum_{s,s',h} OPEX_{s,s',h} \tag{1}$$

$$\begin{aligned} CAPEX = & \sum_{i}\sum_{t} CAP_{i,t} \times UC_{t}^{\text{Capital}} \times CRF_{t} \\ & + \sum_{i}\sum_{s} \lambda_{i,s}^{\text{envelop}} \times UC_{i,s}^{\text{envelop}} \end{aligned} \tag{2}$$

where the subscripts t, k, i represent t kinds of energy technologies, s scenario of energy saving upgrades, and a serial number of buildings, respectively. *CAP* is the installed capacity, *CRF* is the capital recovery rate. UC^{Capital} is the unitary capital cost of different technology types and upgrades, λ is a binary variable representing the choice of a particular energy saving technology.

Considering the scenario tree structure of demand side, the energy saving technologies include the upgrade actions on roof, walls and windows, while one of them and all of them are available to be selected. Hence, for one energy-saving technology, four scenarios can be obtained, i.e., None, Basic, Standard and Premium, which cause various installed cost and heat transfer coefficient. Finally, $4 \times 4 \times 4 = 64$ scenarios constitute the scenario tree structure of demand side.

Moreover, the operation cost can be expressed as follows:

$$OPEX_{s,s',h} = FC_{s,s',h} + MC_{s,s',h} + GC_{s,s',h} \tag{3}$$

where *FC*, *MC*, and *GC* are fuel cost, maintenance cost, and grid electricity cost (including electricity purchasing cost minus electricity feed-back revenue), respectively.

For the scenario tree structure of supply side, the nodes includes typical season, typical day and solar radiation. Based on this, $3 \times 2 \times 2 = 12$ scenarios constitutes the scenario tree structure of supply side.

2.3 Energy balances

The formulation of energy balances is the core element of system constraints. Eq. (4) illustrates that, for the electrical balance in each scenario, the electrical demand is fulfilled by the electrical supply from the internal combustion engine, the battery, the PV panels, the electrical consumption purchased from the bulk grid, minus the electrical consumption of the heat pump and the electrical chiller, while the redundant electricity can be fed into the bulk grid.

$$\begin{aligned} L^{\text{ele}}_{s,s',h} = {} & Q^{\text{ele}}_{\text{pv},s,s',h} + Q^{\text{ele}}_{\text{chp},s,s',h} + Q^{\text{ele}}_{\text{im},s,s',h} + Q^{ele}_{\text{bat-out},s,s',h} \\ & - Q^{\text{ele}}_{\text{ec},s,s',h} - Q^{\text{ele}}_{\text{hp},s,s',h} - Q^{\text{ele}}_{\text{ex},s,s',h} - Q^{ele}_{\text{bat-in},s,s',h} \end{aligned} \tag{4}$$

Eq. (5-6) shows that the heating demand is equal to the sum of heating supply from the internal combustion engine, the gas boiler and discharging of the heat storage tank, minus heating consumption of the absorption chiller and charging of the heat storage tank. Meanwhile, the cooling demand is fulfilled by the absorption chiller, the electrical chiller, and cooling storage.

$$\begin{aligned} L^{\text{heat}}_{s,s',h} = {} & Q^{\text{heat}}_{\text{chp},s,s',h} + Q^{\text{heat}}_{\text{b},s,s',h} + Q^{\text{heat}}_{\text{st-out},s,s',h} + Q^{\text{heat}}_{\text{hp},s,s',h} \\ & - Q^{\text{heat}}_{\text{st-in},s,s',h} - Q^{\text{heat}}_{\text{ac},s,s',h} \end{aligned} \tag{5}$$

$$L^{\text{cool}}_{s,s',h} = Q^{\text{cool}}_{\text{ac},s,s',h} + Q^{\text{cool}}_{\text{ec},s,s',h} + Q^{\text{cool}}_{\text{st-out},s,s',h} - Q^{\text{cool}}_{\text{st-in},s,s',h} \tag{6}$$

2.4 Special operation constraints

Some special operation constraints to be added to the planning model, defining the maximum variation rate of the prime mover between each time-step, i.e. the ramping constraint. The series of the maximum startup constraint limits that the prime mover can only be started at most once per day to ensure the normal life span for the whole period of operation.

$$\left| Q^{\text{ele}}_{\text{ice},s,s',h+1} - Q^{\text{ele}}_{\text{ice},s,s',h} \right| \le 0.5 \times CAP_{\text{chp}} \tag{7a}$$

$$\sum_h \psi_{\text{chp},s,h} \le 1 \tag{7b}$$

$$\psi_{\text{chp},s,s',h} \ge \theta_{\text{chp},s,s',h} - \theta_{\text{chp},s,s',h-1} \tag{7c}$$

$$\psi_{\text{chp},s,s',h} \le 1 - \theta_{\text{ice},s,s',h-1} \tag{7d}$$

$$\psi_{\text{chp},s,h} \le \theta_{\text{chp},s,s',h} \tag{7e}$$

where the Ψ_{chp} and ϑ_{chp} are the binary variables, denoting the startup action and on/off status in one time-step. In this study, the maximum times of startup per day are set as one.

3. CASE STUDY

To demonstrate the proposed model, a case study is conducted for a newly designed business zone in Shanghai, China. Six commercial buildings with network availabilities are illustrated in Fig. 3, where a whole year is divided into summer/winter/transition seasons, cooling is required in summer and heating is provided in winter. In addition, the solar radiation intensity, that will affect the solar PV output.

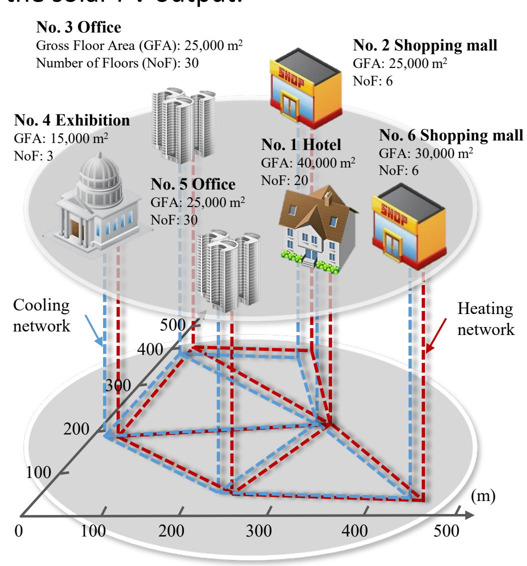


Fig 3 Illustrative the case study of distributed energy system.

The model is established as a Mixed Integer Linear Programming (MILP) model in GAMS, calling Gurobi to solve the model. The entire process is conducted on a small computing server with Intel Xeon and 32 GB RAM.

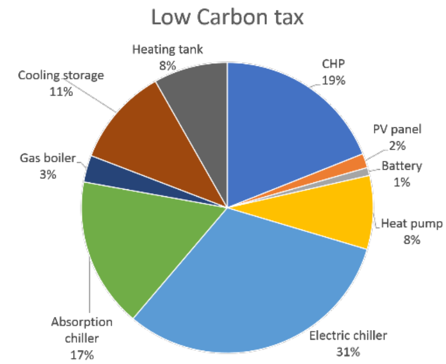
4. RESULT AND DISCUSSION

The optimal solution is obtained by the commercial solver and listed in Table 1. In each level of carbon tax, the optimal configuration chooses to conduct energy-saving technology of demand side rather than the "None" scenario. Meanwhile, the higher carbon tax contributes to the more advanced technology, in which the premium is the common choice for each envelop upgrade. Moreover, due to the difference of the heat transfer coefficient between window, wall and roof, the effect on energy-saving varies. Hence, the selection of envelop upgrade bases on its cost and the effect of energy saving. According to this case, the window has more influence on energy saving, which causes the priority of envelop upgrade.

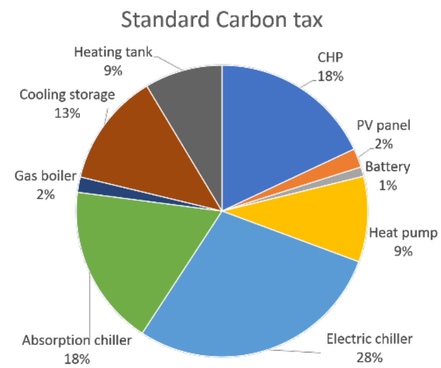
Table 1 Optimal solution for the proposed model.

Installed Capacity	Unit	Value		
		Low Carbon tax	Standard Carbon tax	High Carbon tax
CHP	kW	4512	4250	3975
PV panel	kW	377	495	879
Battery	kW	213	247	476
Heat pump	kW	1953	2237	2741
Electric chiller	kW	7512	6740	4795
Absorption chiller	kW	3971	4211	5237
Gas boiler	kW	712	401	310
Cooling storage	kW	2610	2974	3270
Heating tank	kW	1951	2035	2541
Envelop upgrades	Window	Standard	Premium	Premium
	Wall	Basic	Basic	Premium
	Roof	Basic	Standard	Standard

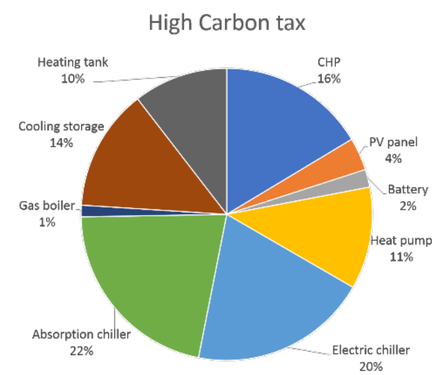
In addition, the optimal system configuration indicates that PV and energy storage devices both show the environmental friendliness, which can be derived from the difference between various levels of carbon tax. Furthermore, the fuel based energy conversion technologies show better economic performance but worse environmental performance. In the scenario of low level carbon tax, the fuel based energy conversion technologies have the highest capacity except for absorption chiller which is always considered as a clean energy technology.



(a)



(b)



(c)

Fig 4 Proportion of each technology of supply side.

Moreover, the optimization of demand-side technology obviously reduces the installed capacity of each supply-side technology, which may save more space for energy station. However, the cost of energy-saving technology needs to be reflected under the condition that the carbon tax is taken into account. Otherwise, the cost reduction of supply side can not offset the cost increase of demand side.

5. CONCLUSION

This study proposes an integrated DES planning model combining supply-side optimization and demand-side optimization. To quantify the various envelop upgrades of demand-side technology, a scenario tree structure is established including wall, window, and roof with different installed cost and heat transfer heat. Based on this, a series of energy demands can be obtained by the building simulation platform, Energyplus. Moreover, another scenario tree is established to consider the solar radiation, typical days, and typical seasons. Furthermore, a DES model is developed as MILP to optimize the total annual cost which is taken the carbon tax into account. The proposed model is built in GAMS, calling the commercial solver, Gurobi. Finally, the optimal system configuration, dispatch strategy, and selection of energy-saving technologies can be obtained and analyzed. Some conclusions can be drawn as follows.

The proposed integrated model enables the design and operation optimization of DES considering energy saving technology on demand side and energy conversion technology on supply side. By introducing the carbon tax into economic performance, the benefit of optimal selection of energy saving technology is obvious, whereas the computational cost increases. Moreover, the level of carbon tax has a great influence on the optimization results of supply side and demand side, which needs the designer to take into account.

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