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GAME THEORY-BASED MODELING AND OPTIMIZATION FOR RENEWABLE MULTI-ENERGY SYSTEM DESIGN

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ABSTRACT

This paper presents a game theory-based modeling framework for government subsidy optimization and renewable multi-energy system (MES) design. The government offers subsidy for renewable technologies, while consumers return rational response to government subsidy on deploying renewable technologies in their respective MES. The game theory-based subsidy optimization and MES design is first formulated as a mixed-integer bilevel nonlinear programming problem and then transformed into a single level mixed-integer linear programing problem using Karush-Kuhn-Tucker conditions and linearization strategies. The results show that the government needs to provide a total subsidy of 3.86 million USD in order to achieve a renewable penetration of 60% in a small urban city composed of four towns. With government subsidy, the total net present costs for the four towns are 8.24, 6.7, 8.32, and 8.93 million USD, respectively.

Keywords: Multi-energy system, Renewable energy, Incentive strategy, Game theory, Bilevel optimization.

NONMENCLATURE

Symbols

CR	Capital refund, USD
$\mathrm{C}^{\mathrm{CAPEX}}$	Capital expenditure, USD
$\mathrm{C}^{\mathrm{OPEX}}$	Operating expenditure, USD
$\mathrm{C}^{\mathrm{npc}}$	Net present cost, USD
$\mathrm{C}_{\mathrm{govn}}^{\mathrm{sub}}$	Government subsidy, USD
PBI	Performance-based incentive, USD
F	Input fuel, kW
P	Output electric power, kW
Q	Output thermal power, kW
m	Waste consumption rate, kg/hr
MW	Waste production rate, kg/d
HHV	Higher heating value, MJ/kg
COP	Coefficient of performance
α	Capital refund ratio
β	Performance-based incentive rate, USD/kWh
θ	Renewable energy penetration
η	efficiency
Ω	Number of design days
r	Interest rate
cgs	Cold gas efficiency
LT	System lifetime, year
Y	Subsidy duration, year
Tdem	Total energy demand, kWh

Subscripts/ superscripts

i	Town
d	Design day
h	Hour
max	Maximum
nom	Nominal
e	Energy technology
$\mathrm{el, th}$	Electrical, thermal

1. INTRODUCTION

Energy and environment have become two major concerns in China. Owing to its prosperous economy, China's energy consumption will be continuously rising. Since coal accounts for China's 70% total energy consumption, the increase in its energy consumption causes severe air pollution especially in northern China. [1] For example, in 2017, residents in northern Chinese cities such as Beijing and Tianjin suffered from the longest stretch of stifling air pollution. They choked through eight days of thick and light-blocking haze. [2] Hence, to mitigate air pollution, it is of necessity to reduce coal consumption and at the same time improve energy utilization efficiency. Multi-energy systems (MES) have become a promising solution, since they are able to increase energy efficiency by cascade utilization and alleviate air pollution via substituting fossil fuels by renewables. However, MES in small or medium scale are quite expensive and may be economically unattractive to urban towns. Hence, government subsidy is necessary to promote their acceptance. Excessive subsidies cause heavy financial burden on government, while insufficient subsidies make residents in towns prefer fossil energy. Hence, how to allocate subsidies and how residents responds to these subsidies become a key issue for MES design.

There are a plethora of works on MES design. They mainly focus on optimizing MES design and operation to satisfy the energy demands of consumers. For example, Mayer et al. [3] designed a hybrid MES for household services using bi-objective optimization and analyzed its economic and environmental performance. Firtina-Ertis et al. [4] examined the optimal sizing of a stand-alone hybrid wind-hydrogen system for zero-energy houses. Accounting for nonlinear behavior and performance degradation of energy technologies, Liu et al. [5] developed a new mixed-integer linear programming model for MES design and operation optimization. Later, they extended this model to address MES long-term planning for an urban town. [6] All these works well addressed MES design for various consumers; however, they took it for granted that consumers will unconditionally deploy renewable technologies to fulfill their energy demands and at the same time meet the targets set for carbon emissions. In practice, consumers may have no interest in renewable technologies if they are too expensive. Hence, to meet the targets of carbon emissions, government intervention or subsidy is needed to promote the acceptance of renewable technologies among consumers. How to capture their mutual interaction is of great importance for subsidy allocation and MES design.

Game theory is able to capture the strategic interaction among rational decision-makers in optimization problems. Particularly, Stackelberg game comprises a leader and one or multiple followers, in which the leader moves first and the followers move sequentially. The leader has full knowledge of the followers and thus can anticipate their actions, while the followers have no means of affecting the leader's actions. Hence, the followers are driven by their respective objectives and respond to the leader's actions by making optimal decisions. The Stackelberg game has a bilevel structure, where the leader makes decisions in the upper level, while the followers optimize their objectives corresponding to the leader's decisions in the lower level. The strategic and rational interaction drives the Stackelberg game to a Nash equilibrium. Hence, it is an ideal framework for studying subsidy allocation and optimizing MES design.

In this work, we develop a game theory-based modeling framework for optimizing government subsidy and MES design for consumers. It determines the optimal subsidy policy of renewable technologies for government and returns the optimal design and operation of MES as well as its capital and operational expenditures for each consumer. Hence, it is valuable for studying subsidy allocation and MES design for both government and consumers.

2. PROBLEM DESCRIPTION

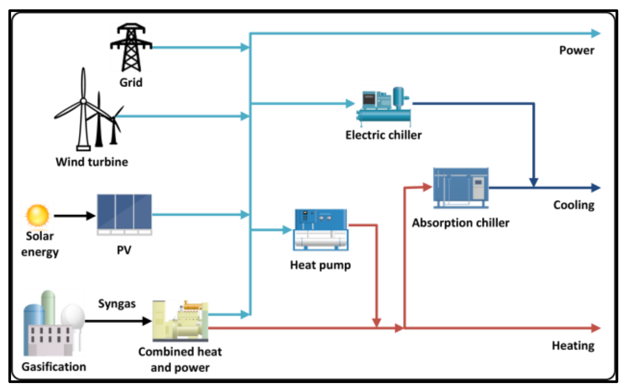

Fig 1 Schematic representation of a renewable multi-energy system.

A schematic representation of a renewable MES is shown in Fig 1. The MES employs photovoltaic (PV) panels, wind turbine (WT), and a gasification-based combined heat and power (CHP) engine as primary energy technologies. Moreover, it can purchase electricity from power grid if necessary. The gasifier produces syngas from biomass such as agricultural, forestry, and municipal wastes. The syngas is cleaned and purified and then sent to the CHP system for electric and thermal power generation. The electricity from PV, WT, CHP and power grid can be used to drive electric chiller (EC) and heat pump (HP) for producing cooling and heating, respectively. An absorption chiller (ABC) is included to utilize the surplus thermal power during CHP operation. The excessive electricity and heating can be exported to power and heat networks. The problem of game theory-based MES design is to determine the optimal subsidy policy of each renewable technology for government to fulfill its targets and the optimal design and operation of MES for each consumer (here refers to an urban town) corresponding to the government subsidy.

3. METHODS

3.1 Model formulation for leader

The government subsidizes each town through capital refund and performance-based incentives to promote renewable acceptance. Capital refund refers to a return of some payments for investing renewable technologies $e \in \Theta_1 = \{PV, WT, CHP\}$ to each town, i. The capital refund of a piece of renewable technology can be expressed by its refund ratio (α_e) as follows:

$$CR_{i,e} = \alpha_e C_{i,e}^{CAPEX} \quad e \in \Theta_1 \tag{1}$$

The performance-based incentives (PBI) are incentives paid to each town based on the cumulative energy production of its renewable technologies. Generally, PBI can take a variety of forms, depending on the administrative abilities of granting these incentives. For example, a feed-in tariff is a typical form of PBI. In this work, PBI takes the form of incentive rate (β_e) and is granted to each town based on the cumulative energy production of its renewable technology *e*.

$$PBI_{i,e} = \beta_e \sum_{d=1}^{D} \Omega_d \sum_{h=1}^{H} P_{i,e}^{d,h} \quad e \in \Theta_1 \tag{2}$$

By implementing capital refund and PBI, the government aims to achieve a desirable target (θ) of renewable penetration as assured by Eq. (3).

$$\sum_{i\in I} \sum_{e\in\Theta_1} \sum_{d=1}^{D} \Omega_d \sum_{h=1}^{H} \left(P_{i,e}^{d,h} + Q_{i,e}^{d,h}\right) \geq \theta * Tdem \tag{3}$$

The government minimizes its total subsidy as defined in Eq. (4) over the subsidy duration (Y) so that its target is met with minimum costs.

$$C_{govn}^{sub} = \sum_{i,e} \left(CR_{i,e} + \sum_{y\in Y} \frac{1}{(1+r)^y} PBI_{i,e} \right) \tag{4}$$

3.2 Model formulation for followers

The followers respond to the leader's actions to determine the selection and sizing of energy technologies as well as their operation profiles in their respective MES. The modeling of PV and WT can be found in our previous works [5,6]. The gasification-based CHP system comprises a gasification subsystem, a gas turbine, and a waste heat recovery subsystem. The gasification subsystem uses municipal wastes as feedstock to produce syngas. The wastes go through a series of processes (i.e. drying, pyrolysis, combustion, and gasification) and are finally converted into syngas. The syngas is cleaned in the downstream processes and then burned with air to drive the CHP system for simultaneous electric and thermal power production. Given electric power demand, its input fuel and output thermal power can be determined as follows:

$$P_{i,CHP}^{d,h} = \eta_{el,CHP}^{nom} \cdot cgas \cdot HHV \cdot m_{i,w}^{d,h} \tag{5}$$

$$Q_{i,CHP}^{d,h} = \eta_{th,CHP}^{nom} \cdot cgas \cdot HHV \cdot m_{i,w}^{d,h} \tag{6}$$

The waste consumption ($m_{i,w}^{d,h}$) needs to be constrained as follows:

$$\sum_{h=1}^{H} m_{i,w}^{d,h} \leq MW_i^d \tag{7}$$

The relationships between their input fuel and output power of conversion technologies (HP, ABC, EC) can be expressed as:

$$F_{i,e}^{d,h} = Q_{i,e}^{d,h} / COP_e^{nom} \tag{8}$$

The size and operation of each energy technology need to be limited by Eq. (9).

$$P_{i,e}^{d,h}(Q_{i,e}^{d,h}) \leq P_{i,e}^{nom}(Q_{i,e}^{nom}) \leq P_{i,e}^{max}(Q_{i,e}^{max}) \tag{9}$$

Energy balance is performed for electricity, heating, and cooling with export of electricity and heating to ensure that energy demands are always satisfied.

The objective of each town is its total net present cost, which is determined by subtracting the government subsidy from its total capital and operating expenditures over system lifetime (LT), as shown in Eq. (10). The computation of total capital and operating expenditures can be found in our previous work [5].

$$C_i^{npc} = C_i^{CAPEX} + \sum_{y \in LT} \frac{1}{(1+r)^y} C_i^{OPEX} - C_{govn}^{sub} \quad (10)$$

4. CASE STUDY

A small urban city composed of four towns in Tianjin, China is used here for demonstrating the game theory-based MES design. The government offers subsidy to promote renewable energy penetration and reduce reliance on fossil energy. Each town deploys renewable technology based on government subsidy and other energy technologies to satisfy its electricity, heating, and cooling demands. The game theory-based MES design problem is a mixed-integer bilevel nonlinear programming (MIBNLP) problem and cannot be solved by any existing commercial optimizers. We reformulate the MIBNLP problem into a single level mixed-integer linear programming (MILP) problem by using Karush-Kuhn-Tucker (KKT) conditions and linearization techniques. The reformulated MILP problem is solved using Gurobi optimizer in GAMS on a laptop with Intel Core I7-6500U CPU, 8 GB RAM, and 64 bit Windows 7 operating system.

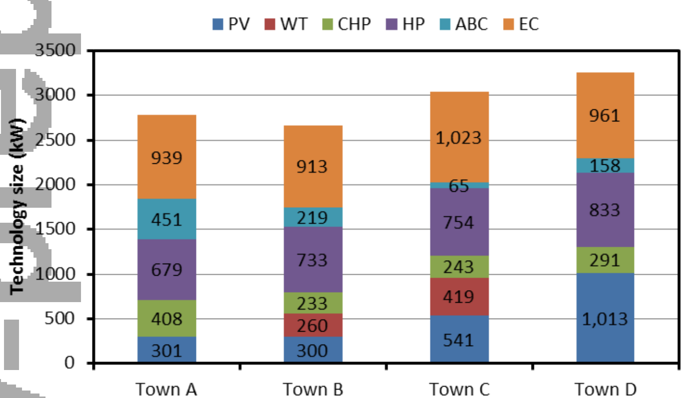

Fig 2 Size of each tehnology in each MES.

5. RESULTS AND DISCUSION

5.1 *Optimal government subsidy and MES design*

The capital refund ratio and PBI rate for PV (WT) are determined to be 20% (7.5%) and 0.035 (0.07) USD/kWh, respectively. There are no capital refunds and PBI for gasification-based CHP system, as it is economically feasible with the current cost parameters. The size of each energy technology in each MES is shown in Fig. 2. As can be seen, WT is not adopted in Town A and D, since its refund ratio and incentive rate are relatively low. Moreover, CHP and PV installed in these two towns along with the imported electricity are able to cover the electricity demands. CHP (ABC) coordinates with HP (EC) to meet the heating (cooling) demands; hence, HP (EC) is sized larger if CHP (ABC) has a relatively small size. This drives MES to be a complementary system for delivering power, cooling, and heating. The total government subsidy and total net present costs for the four towns are 0.37 (8.24), 0.84 (6.7), 1.41 (8.32), and 1.24 (8.93) million USD, respectively, achieving a renewable penetration of 60% in the small urban city.

5.2 *Optimal MES operation*

Fig. 3 shows the electricity generation of each technology in MES. CHP, PV, and WT are the main suppliers of electricity. They coordinate with the imported electricity to fulfill the electrical demands of consumers. Meanwhile, the excess electricity can be exported or used to drive HP and EC for producing heating and cooling, respectively. For instance, town A exports a fraction of electricity at 0:00-6:00. Moreover, in winter day, town B imports electricity at 0:00-6:00 for driving HP to provide heating. The total annual exported electricity reaches 186.7 MWh.

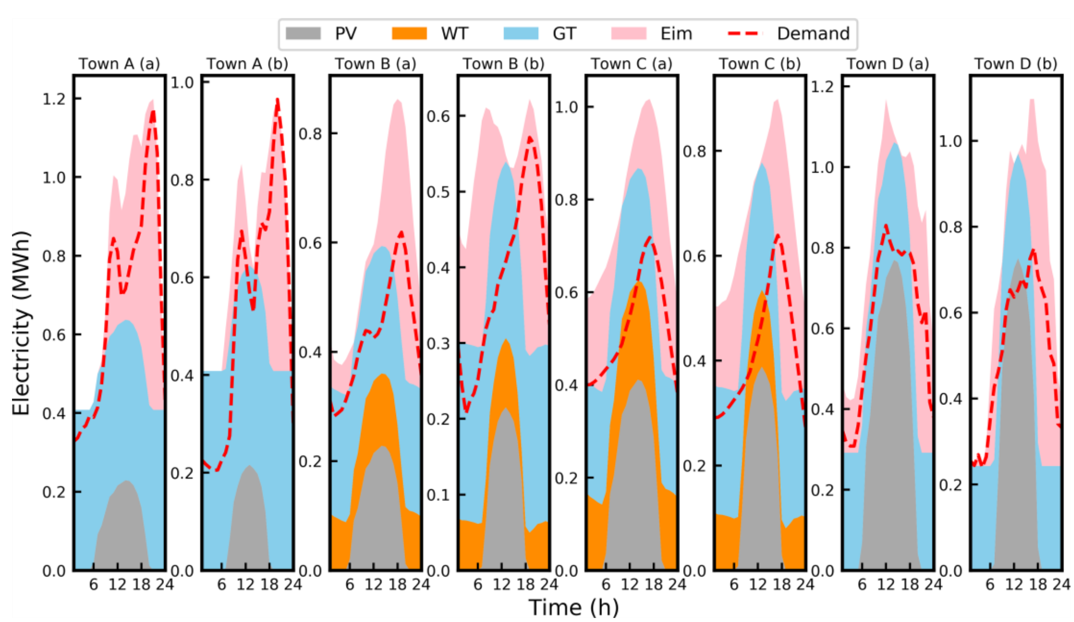

Fig 3 Electricity generation of MES in the four towns: (a) summer day and (b) winter day.

The heating generation matches heating demands of consumers quite well in winter days as shown in Fig. 4. Moreover, CHP provides constant heating capacity, while HP ramps up and down to deliver extra heating power to meet the heating demands. HP are nearly turned off in summer day, and excess heating power from CHP can be exported or utilized to drive ABC to producing cooling as can be seen in Fig 4. The total annual exported heating for the four towns is 216.8, 32.6, 86.5, and 40.6 MWh, respectively.

EC, a main supplier of cooling, coordinates with ABC to meet the cooling demands of consumers as can be seen in Fig. 5. EC ramps up and down to cover the cooling deficit in summer and winter days. Only a fraction of CHP thermal power is used to drive ABC for producing cooling, as exporting some of its thermal power minimizes total cost of each consumer. Moreover, EC tends to cover all the cooling demands in a winter day, as its cooling is relatively low and CHP thermal power is mainly used to provide heating.

6. CONCLUSIONS

This work presented a game theory based modeling framework for optimizing government subsidy and renewable multi-energy system design. The capital refund ratio and performance-based incentive rate for PV (WT) are determined to be 20% (7.5%) and 0.035 (0.07) USD/kWh, respectively. Thus, the government needs to offer a total subsidy of 3.86 million USD in order to achieve a renewable penetration of 60% in the small urban city. With government subsidy, the total net present costs for the four towns are 8.24, 6.7, 8.32, and 8.93 million USD, respectively. Therefore, we can conclude that proper subsidy can promote renewable acceptance and achieves a renewable and sustainable energy system.

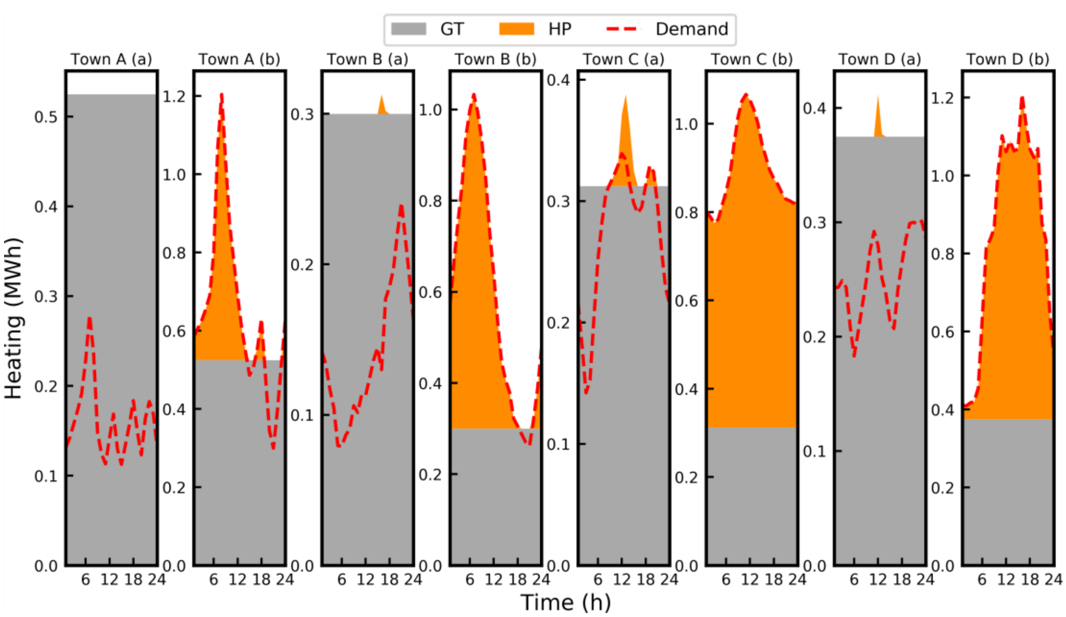

Fig 4 Heating generation of MES in the four towns: (a) summer day and (b) winter day.

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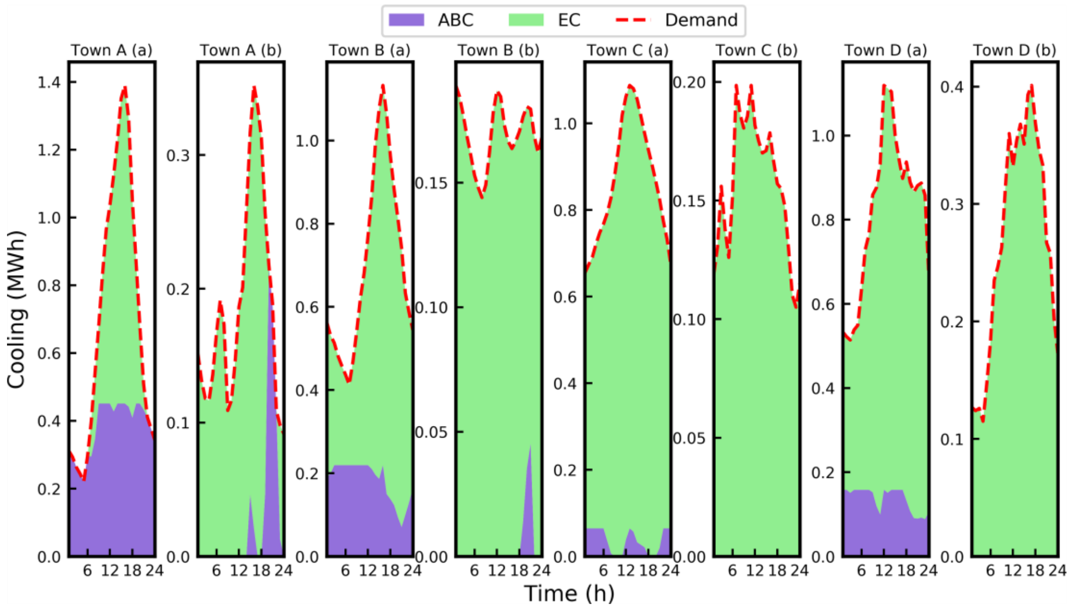

Fig 5 Cooling generation of MES in the four towns: (a) summer day and (b) winter day.