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A SYSTEM VALUE APPROACH QUANTIFYING THE CONTRIBUTION OF INDIVIDUAL ENERGY TECHNOLOGIES IN INTEGRATED URBAN ENERGY SYSTEMS

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ABSTRACT

Most of studies quantified the energy technology cost of integrated urban energy systems by calculating the levelized cost of energy (LCOE), but few analyze the contribution that an individual technology can bring to whole complex systems. This study introduces a generalized "system value" approach to quantify the contribution of each individual technology to the whole system as a function of the individual's installed capacity. A generalized urban energy system optimal design model is formulated by Mixed Integer Linear Programming (MILP). An illustrative case study is conducted to explore the system values of different urban energy technologies. The results indicate that combined heating and power (CHP) presents the largest system value among all technologies. Heating/cooling supply technologies tend to provide lower system values compared to other electricity supply technologies due to the offset effect from adoption of energy saving strategies. Additionally, an individual technology's system value varies with different penetration levels of that technology. Overall, this study presents a formulized method to assess the contribution of an individual technology from a systemic perspective, and aims to provide a new standpoint for decision-makers (instead of LCOE) for evaluating new technologies' integrations to complex systems.

Keywords: system value; LCOE; integrated urban energy system; energy saving strategies; MILP

NONMENCLATURE

Abbreviations

MILP	Mixed Integer Linear Programming
LCOE	Levelized cost of energy
CHP	Combined heating and power
UES	Urban energy system
SV	System value
PV	Photovoltaic
Symbols	
i	building index
j	building index
s	season
h	hour
k	energy saving options
ϕ	binary variable
$Q^{c\text{-}dem}$	original cooling demand
$Q^{c\text{-}win}$	saving by implementing window upgrade
$Q^{c\text{-}roof}$	saving by implementing roof upgrade
$Q^{c\text{-}wall}$	saving by implementing wall upgrade
Q^{cha}	cooling charge into a cooling storage
Q^{disc}	cooling discharge
$Q^{ec\text{-}cool}$	electrical chillers cooling supply
$Q^{ac\text{-}cool}$	absorption chillers cooling supply
$Q^{cf(i,j)}$	cooling flow from building *i* to *j*
$Q^{cf(j,i)}$	cooling flow from building *j* to *i*
$Lo^{c\text{-}pipe}$	cooling transfer loss constant

1. INTRODUCTION

Urbanization is one of the global processes that would have significant impact of human living conditions and global warming. As the share of people living in urban areas grows world-wide, larger amount of energy is required to energize the urban areas, particularly for commercial and residential buildings [1]. Hence, urban

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energy systems (UES) play a key role for mitigate the greenhouse gas emissions. The UES becomes more complex gradually as more decentralized energy technologies are developed. Within such complex systems, valuation of a certain technology becomes particularly important for analyzing the penetration of one technologies into a system. Many studies have analyzed the least energy cost system design by optimizing the model with the objective function of LCOE [2, 3]. Definition of LCOE can be found in the study conducted by Schmidt et al. [4], who projected the LCOE of 9 electricity storage technologies in 12 possible applications. Kitapbayev et al. [5] investigated the flexibility that thermal storage can bring to district energy systems in terms of LCOE considering the stochastic price of electricity and gas. Gottwalt et al. [6] utilized LCOE to rank the residential demand response availability of different technologies with an increasing share of renewable energy in the energy mix.

Although a least cost design can be achieved by optimizing the corresponding model, the contribution of individual technology to that objective is not always clear. Hence, a systematic valuation methodology for UES deserve an investigation, leading to new insights.

2. METHODOLOGY

This paper introduces the “system value” approach to quantify the contribution of various urban energy technologies for the whole system from a systematic perspective. The system value (SV) of a technology is defined as the marginal benefit that the technology can bring to the whole system as a function of its installed capacity.

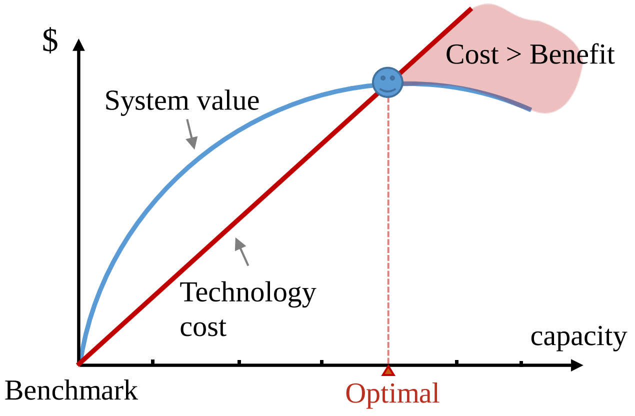


Fig 1 Definition of system value.

As shown in Fig. 1, the energy cost is selected as the measure for “system value” Based on the benchmark where a certain technology is excluded from the optimal system configuration, the system value is the cost reduction caused by the incremental installation of that technology. The maximum system value is expected to be obtained when the installed capacity reaches its optimal value in the original model. If the installed capacity is over that optimal value, the system value is expected to drop. To evaluate system values of diverse technologies, a generalized modelling framework for optimal design of UES is developed. Due to the content limits, only the cooling balance is displayed in Eq. 1 as an example of integrating energy saving strategies with energy supply technologies. The rest of the model can be found in our previous publications [7].

$$\begin{aligned}&\mathrm{Q}_{i,s,h}^{\text{c-dem}}-\sum_{k=1,2,3}\varphi_{i,k}^{\text{win}}\times\mathrm{Q}_{i,s,h,k}^{\text{c-win}}-\sum_{k=1,2,3}\varphi_{i,k}^{\text{roof}}\times\mathrm{Q}_{i,s,h,k}^{\text{c-roof}}\\&-\sum_{k=1,2,3}\varphi_{i,k}^{\text{wall}}\times\mathrm{Q}_{i,s,h,k}^{\text{c-wall}}+Q_{i,s,h}^{\text{cha}}+\sum_{j}Q_{i,j,s,h}^{\text{cf}(i,j)}=Q_{i,s,h}^{\text{ac-cool}}\\&+Q_{i,s,h}^{\text{ec-cool}}+\sum_{j}Q_{j,i,s,h}^{\text{cf}(j,i)}\times(1-\mathrm{Lo}^{\text{c-pipe}})+Q_{i,s,h}^{\text{disc}}\quad\forall i,j,s,h,j\neq i\end{aligned}\tag{1}$$

where the left-side of cooling balance includes cooling demand ($Q^{\text{c-dem}}$); potential cooling demand reduction ($\mathrm{Q}^{\text{c-win}}$, $\mathrm{Q}^{\text{c-roof}}$, $\mathrm{Q}^{\text{c-wall}}$) by implementing energy saving strategies on window, roof, and wall, respectively; cooling charge (Q^{cha}) into a cooling storage; and cooling flow transferring from building *i* to *j* ($Q^{\text{cf}(i,j)}$). The right-hand side consists of cooling supply from electrical chillers ($Q^{\text{ec-cool}}$) and absorption chillers ($Q^{\text{ac-cool}}$); cooling flow from building *j* to *i* ($Q^{\text{cf}(j,i)}$); and cooling discharge (Q^{disc}) from cooling storage. The cooling transfer loss is also considered by a cooling loss rate ($\mathrm{Lo}^{\text{c-pipe}}$). φ is the same binary variable to control the selection of energy saving options as in the heating balance. The potential cooling demand reduction ($\mathrm{Q}^{\text{c-win}}$, $\mathrm{Q}^{\text{c-roof}}$, $\mathrm{Q}^{\text{c-wall}}$) are pre-calculated parameters to keep the entire model linear.

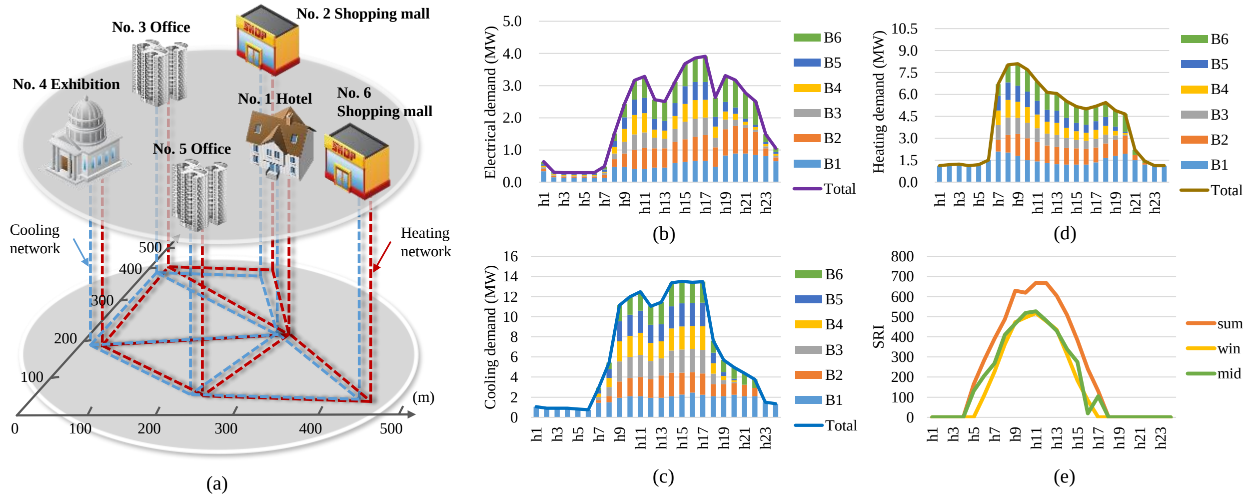
3. CASE STUDY

A case study is conducted in a business zone (with 6 large commercial buildings) in Shanghai, China for designing an urban energy system. Electrical, heating and cooling energy demands are fulfilled simultaneously. The case is appropriate to demonstrate the methodology as it allows: 1) free connections to the grid and each other, 2) enables common energy supply technologies and saving strategies including the renewable and storage techniques. By giving the optimization model maximum freedom, the best network and system configuration design, as well as the operational strategy, only reply on the optimization results, which intend to demonstrate each technology’s system value in a generalized manner.

The locations and categories of buildings, energy demand, as well as solar radiation index (SRI) are presented in Fig. 2.

4. RESULTS AND DISCUSSION

Each technology brings different amounts of system value to the whole system as shown in Fig. 3. None of the system value curves show a linear correlation with the incremental installed capacity. This indicates that every unit of one technology added to an existing configuration will bring different amounts of benefit than other units. The system value method is a good measure for this phenomenon and is contrasted with LCOE.



(a)

(b)

(c)

(d)

(e)

Fig 2 building categories, electrical heating cooling demand and solare radiation index of the case study.

Electricity supply technologies tend to have larger system value compared to heating and cooling supply technologies. Adoption of energy saving strategies can efficiently reduce cooling/heating demand, to avoid installing larger capacities of heating and cooling technologies, which further leads to less system value achieved by heating and cooling technologies. The trade-off exists between implementing energy saving strategies and installed larger capacity of energy supply technologies.

CHP brings the largest amount of system value (US$ 750×103) to the whole system as shown in Fig. 3(a) as it supplies both electricity and heating simultaneously. As for PV panels, due to the practical limit on available installation space, they bring a limited maximal system value of US$ 39×10^3. However, the trend of system value curve as shown in Fig. 3(b) indicates that more value could be brought to the whole system if larger space of PV installations is available. Seen in Fig. 8(c), although a relatively small capacity of electricity storage (i.e., battery) is adopted in the optimal system configuration, it brings a significant amount system value. Meanwhile, its system value is sensitive to its installed capacity, which may not take effect if the installed capacity is not large enough. Hence, the system designer should be very cautious about the sizing of the battery storage. Comparing cooling storage as shown in Fig. 8(e) with the battery storage, although a significantly larger capacity of cooling storage is adopted, the system value (i.e., US$ 63×10^3) it can bring is even slightly less than that of the battery storage. As for the heating supply technologies, heat pumps can only bring a maximal system value of US$ 35×10^3 as shown in Fig. 3(d), and boilers bring even lower amount of system value of US$ 8.2×10^3 as shown in Fig. 3(e). The reason why heating supply technologies bring limited system value is due to the availability of multiple energy saving strategies.

5. CONCLUSIONS

This paper brings a preliminary introduction of a system value approach that can measure the individual contribution of one technology penetrating into a whole system. the effectiveness of the approach is demonstrated by a case study where a generalized urban energy system (UES) model is established including 9 energy supply technologies and 3 energy saving strategies. The results indicate that different technologies can bring different amount of system values. Even for one certain technology, the system value varies with different penetration levels of that technology. Meanwhile, the combined heating and power (CHP) presents the largest system value among all technologies. Heating/cooling supply technologies tend

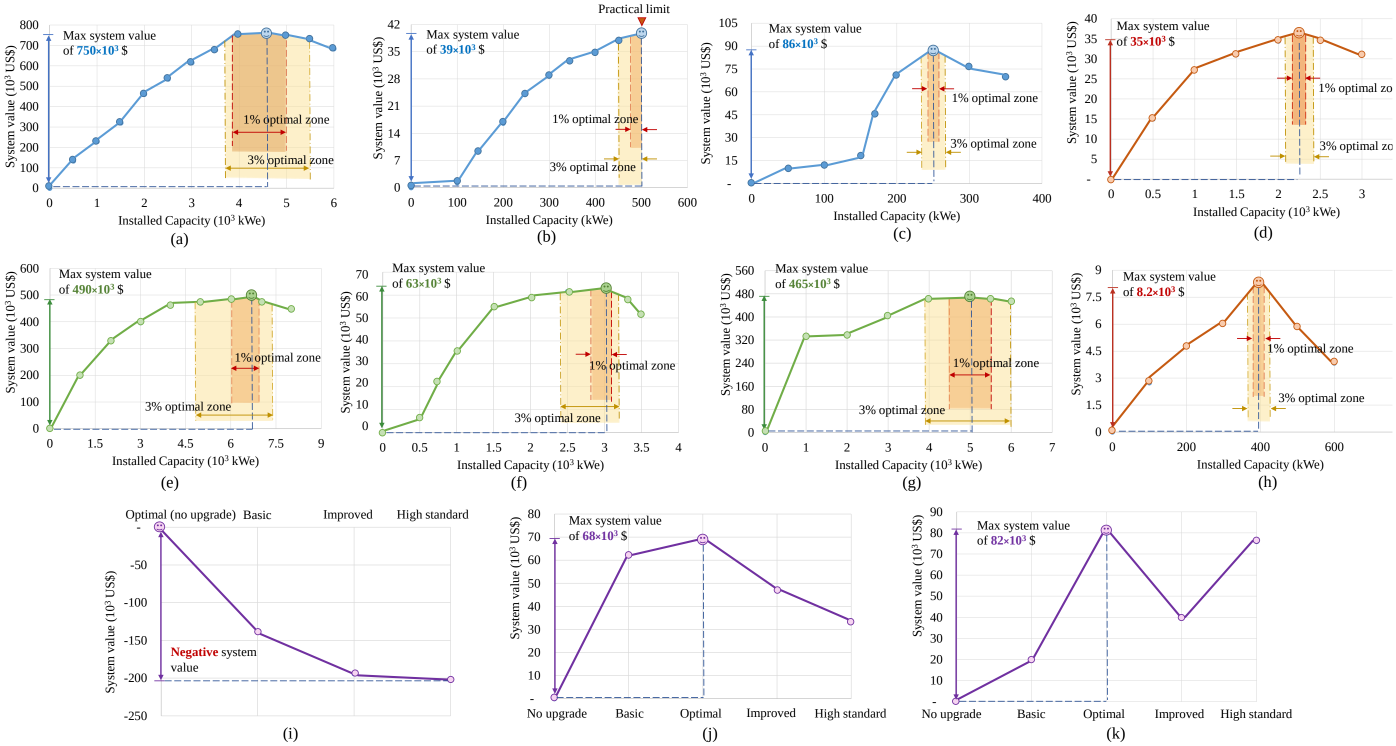


Fig 3 System value of various energy supply technologies and energy saving strategies.

to provide lower system values compared to other electricity supply technologies due to the offset effect from adoption of energy saving strategies.

Overall, this study presents a formulized method to assess the contribution of an individual technology from a systemic perspective.

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