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The energy-saving potential of an office under different pricing mechanisms – Application of an agent-based model

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HIGHLIGHTS

- An agent-based model is developed to simulate the energy consumption of offices.
- Different pricing mechanisms and people's maximum-saving behavior are simulated.
- The detailed features of various types of appliances are carefully analyzed.
- Offices have huge energy saving potential, i.e. 24.5%, without technical investment.

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ABSTRACT

This paper developed an agent-based model (ABM) to explore the energy saving potentials (ESPs) of various types of appliances in offices under different pricing mechanisms. The model included four types of commonly used appliances in office buildings: an air conditioner (AC), computers, lights and a basic load. The total ESPs of the entire office are 6.7% and 17.4% on the second and the third price tier of the tiered pricing mechanism (TEP), while the ESPs are 11.8% and 14.2% under the peak-valley pricing (PVP) and critical peak pricing (CPP), respectively. Within different types of appliances, AC consumes the largest amount of electricity, over 50%, while the ESPs of the AC under different pricing mechanisms are only 6.9–12.1%. In contrast, the lights have the biggest ESP, i.e. 14.1–53.4%, under various pricing levels. Both the pricing mechanisms of PVP and CPP only have the effect of peak clipping and do not have a significant effect of valley filling, since there is no people working in the office during the valley price period. The maximum ESP, which is based on people's maximum-saving behavior, is much larger than the ESPs on the basis of people's ordinary consumption patterns. This implies the importance of improving people's awareness of energy saving and refining their behaviors. Lastly, the model developed in this study provides a generic platform for simulating many types of energy systems and is very effective for handling the complicated relations between different types of technology and the way how they are used and interacted with each other. ABMs have very good adaptability and capacity in simulating energy systems.

1. Introduction

Energy consumption is increasing every year and this results in heavy ambient pollution and global warming. Building sector accounts for nearly 50% of the total energy consumption worldwide and the number is still increasing along with the economic development and urbanization [1]. In particular, public buildings such as office buildings, hotels and shopping malls contribute to a majority of electricity consumption in urban cities [2]. Therefore, it is crucial to explore the energy saving potential (ESP) in public buildings.

The energy consumption in buildings is mostly decided by the performance of electric appliances and how they are used. In office buildings, the electricity consumption mainly includes the consumption of office equipment, HVAC (heating, ventilation, and air-conditioning) systems and lighting systems. Previous research on the electricity consumption in buildings focused on the consumption of different categories of electric appliances. [3–5] divided appliances based on their consumption patterns and studied how much different electric appliances contribute to electricity consumption. [6–8] divided appliances based on their specific functions and influence factors. In various categories of electric

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appliances, lots of research [9–12] focused on the electricity consumption of HVAC systems. However, the existing literature seldom comprehensively consider the interactions between different appliances, the construction features of buildings and the outdoor environment.

Many methods have been employed to reduce the electricity consumption of electric appliances in public buildings. In summer, air conditioners (ACs) accounts for about 30–50% of the total electricity consumption in buildings [13]. Green roofs [14] and well-designed envelope configurations [15] are proved to be able to reduce heat flux into buildings and thus the electricity consumption of ACs. To reach the same indoor temperature, [16] examined the effects of variable-speed ACs and [17] tested water-based cooling systems to lower down the electricity consumption. In addition to ACs, the energy consumption of other appliances, e.g. lighting system occupies 20–40% of public building's energy consumption and could be reduced by 50–80% with system updating [18]. However, these approaches are mainly technical solution, while the energy consumption patterns, namely how the technologies are used has been rarely considered [19,20].

Energy consumption pattern is another important factor influencing on the energy consumption in buildings [21,22]. Energy consumption patterns, closely related to occupants' behavior, are featured by individual randomness and collectively clustering [2]. However, in order to reduce the complexity related to the occupants' random actions, existing studies usually modelled occupants' behavior in a pre-defined way and hardly consider the impacts of occupant's interactions on their further actions [23–25]. Regarding the control of electric appliances, existing studies have separately investigated how HAVC systems could be adjusted to meet the requirement of indoor thermal comfort [26] and how lights could be controlled to provide a suitable level of illumination [27]. However, very few studies have comprehensively investigated how these appliances should be used to save energy without lowering down the indoor comfort or illumination and no study has carefully compared the ESPs of different types of appliances.

Energy price is also an important factor that can affect energy consumption, typically by changing energy consumption patterns. Governments may employ different pricing mechanisms in order to achieve certain policy targets on the market [28]. In China, the pricing mechanisms on the electricity market include tiered pricing (TEP), which is also called multi-step pricing, peak-valley pricing (PVP) and critical peak pricing (CPP) [29]. Different from the European market, the time-of-use (TOU) pricing mechanism has so far not been widely adopted in China. TEP was implemented in China four years ago and its active effects on reducing residential consumption has been widely recognized [30,31]. CPP is defined on the basis of PVP, namely under CPP three hours in peak time are defined as 'critical peak time' and the electricity price in critical peak time is even higher than the price in peak time. CPP is used only in summer. PVP and CPP can help to shift the loads of electricity consumption [29,32,33]. Various pricing mechanisms have different influences on the patterns of energy consumption [34]. Many existing studies tended to look into the psychological reasons to explain how people would change their behavior due to a certain size of price change. It is very difficult to get a reliable result simply because people are heterogeneous. However, an effective method is to cluster people into groups according to their behaviors and further to describe the energy consumption patterns according to the main features of a group [35]. The heterogeneity of people can be expressed by people's random behavior in simulation models like Agent-based Models (ABMs) [36].

ABMs are becoming increasingly popular for simulating energy systems, especially those involving high level of randomness, complicated actions of individual units and their interactions and a comprehensive system environment with both exogenous and endogenous parameters [24,37,38]. The individual units are called agents in an ABM, which can take actions in a pre-defined modeling environment. The actions taken by one agent may affect other agents or the environment, the reactions of other agents and the environment can further affect the agent's actions in the future. Agents can represent occupants and appliances and the actions of agents will thus cause energy consumption in an energy system [4,39]. Although the past decade witnessed the rapid development of ABM in energy research, the ABMs are still limited in complexity regarding the type of agents, the variety of their behaviors and the interactions between agents and between agents and the environment.

Therefore, the aim of this paper is to explore the ESPs of various types of appliances commonly used in offices. To this aim, an ABM, which involves 5 types of agents: 20 lights, 20 computers, an AC, a basic load and 20 occupants, were developed to study the electricity consumption of an office room. The operation of the appliances and their interactions were simulated in the model. The electricity consumption of different appliances under the single price mechanism (SGP) was taken as the reference case, where multiple setting temperatures for the AC were considered. Then, the study simulated the electricity consumptions under the CPP, PVP and TEP, respectively. The results were compared with the reference case to calculate the ESPs. In addition, the paper further studied effects of load shifting under different pricing mechanisms and the maximum ESP of the office, which relies on the maximum-saving behavior of the occupants. Suggestions on how electricity consumption can be reduced in offices are provided after the analysis.

The contributions of the paper are two-fold. On one hand, the paper employs an ABM to study the energy consumption in offices and this provides a relatively new approach to analyze energy consumption in public buildings. The detailed features of various types of appliances, as well as their ESPs, are carefully analyzed. On the other hand, the ABM in the present study include electric appliances and consumers, which respectively represent low-level and high-level intelligent agents in an ABM. The mixture of different types of agents with different levels of intelligence, as well as their comprehensive interactions, is one of the central issues for the methodological development of ABM.

2. Methodology

This study developed an ABM for an office room to simulate its electricity consumption. The fundamental components of an ABM include the agents and their behaviors. In this study, the ABM defines five types of agents: 20 electricity user agents, 20 computer agents, 20 light agents, an AC agent and a basic load agent. Every agent has its individual states and rules of behavior, which will be introduced later. It is worth mentioning that the study looked at the most common types of office appliances in order to obtain general results that can be widely applied elsewhere. The model studied the energy consumption in summer to obtain a deep understanding about the operation of the AC in contrast with other appliances. The ABM was implemented in the software AnyLogic with a time step of one second [40].

The empirical data in the model was based on an investigation about an office in the Qianfoshan campus of Shandong University, Jinan, China. We have carried out a survey (questionnaire and observation) to investigate the energy using behavior of the users and the electricity consumption of the electric appliances. The questionnaire was handed out to 300 staff and graduate students working in the office building. In total, we have received 237 valid responses (response rate = 79%). The studied office is a typical office room in China, where many Chinese university staff and graduate students stay and work from early morning to late eve-