The strategy of building energy consumption based on the carbon emission trading system under stochastic dynamic scenario

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Abstract

To achieve the "dual carbon goals" in building sector, the paper presents a novel building energy consumption strategy model during the operational phase based on the emission trading system (ETS). In the context of distributed grid layout, the best energy consumption strategy obtained by building users using stochastic dynamic programming (SDP) based on real-time electricity prices and carbon trading prices and their own energy consumption preferences. This makes the whole problem of multi-objective optimization including carbon trading and the cost of building operation. In this paper, the model is used to analyze a Chongqing building, and the sensitivity analysis of carbon permits costs is made. The results show that, (1) the cost of building carbon emissions has a significant impact on the operation of the building; (2) the user's energy consumption strategy can also affect operating costs; (3) the ETS achieves near-zero emissions while increasing building operating costs. This shows the importance and effectiveness of the ETS in the realization of "dual carbon goals" in building sector, and the value of building users actively developing energy consumption strategy.

Keywords: Emission trading system, Building energy consumption, Stochastic dynamic programming, Demand-side management

1. INTRODUCTION

Worldwide climate shifts, marked predominantly by increasing global heat, stand as one of the most significant obstacles to human civilization in this century (Fang et al, 2011). The Paris Agreement set the goal of pursuing efforts to keep the world within +1.5ºC of warming. The growing levels of CO_2 in the atmosphere are thought to be closely linked to shifts in climate patterns, most notably global temperature increases (Malik et al, 2016). China, recognized as the world's top emitter of greenhouse gases, assumes a pivotal responsibility in addressing the global climate crisis. Among them， the Chinese government has committed to reaching its peak carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060. Decarbonizing the buildings and construction sector is essential, as this sector accounts for nearly 40% of energy and process-related emissions (IEA, 2019).

China has released Guidelines for the identification and evaluation of zero carbon buildings 2021 to promote the realization of dual carbon goals in the building sector. The guidelines include the carbon emissions related to the operational aspects of buildings, which represent the bulk of CO_2 emissions over the course of a building's life cycle. These emissions primarily mirror user practices and the broader societal dependence on fossil fuels, especially for the production of electricity (Junnila et al., 2006; Kofoworola et al., 2008). Heating, ventilation, air conditioning (HVAC) systems, lighting, various equipment, and household appliances are identified as the primary categories responsible for the highest levels of energy usage (Biswas, 2014; Kofoworola et al., 2008). The progress in renewable energy technologies, combined with the implementation of passive design strategies, has contributed to a gradual decline in carbon emissions during the building's operational period (Fenner et al., 2018). Recently-built net-zero energy buildings that combine the use of these strategies are known for their minimal impacts in the operational stage (Shao et al., 2014; Marszal et al., 2014). Considering the high density of urban residents, it's hard to achieve net zero emissions by individual buildings for the limited rooftop. Distributed energy systems (DESs) can be adaptively organized around buildings in response to the varying energy requirements of users (Ma et al., 2020), a fact that has been extensively acknowledged and promoted. Liu et al. (2022) designed an innovative distributed energy system that integrates hybrid energy storage solutions with optimally harnessed renewable energy sources.

Implementing a price on emission-producing products is also considered an effective approach to diminish resistance to emission reduction (Khaqqi et al., 2018). Carbon taxes and tradable permits represent two widely acknowledged mechanisms for imposing a price on the production of emissions (Spulber, 1985). The tradable permits policy is also referred to as the emissions trading scheme (ETS) or cap-and-trade system (Khaqqi et al., 2018). Carbon tax might serve as an efficient tool for cutting CO2 emissions (Jiang and Shao, 2014), but it is relatively harder to manage emission outcomes compared to carbon trading, where a cap exists in the ETS market (Qian et al., 2017). The Chinese government officially introduced an ETS in 2011. Seven regions were initiated as carbon trading pilots, and now, China has fully launched a national carbon market. Five of the seven emissions trading scheme (ETS) pilot programs have extended their scope to include the building sector (Swartz, 2016). Despite this expansion, no substantial carbon trading activities have been observed in building-related projects (Wang et al., 2017). A key barrier to participation by building owners in the ETS market is the transaction cost, which plays a decisive role in their willingness to engage (Song et al., 2018). Several factors contribute to the lack of active ETS trading within the building sector. First, the transaction costs for individual buildings are relatively high because the carbon reduction per building is significantly smaller than in other industrial sectors, such as power plants, where reductions are achieved on a much larger scale (Lam et al., 2015). Additionally, the scattered ownership of units within buildings, such as residential properties, further complicates the participation of the building sector in carbon trading markets (Raines et al., 2005). These challenges highlight the complexities of integrating the building sector into the ETS framework.

Advancements in science and technology, particularly the rise of blockchain technology, have contributed to lowering the barriers to entry for the carbon trading market, which make individuals have the opportunities to participate in low-carbon economy (Pan et al., 2019). This study assumes that buildings possess distributed energy systems (DESs) and have the ability to trade their excess or conserved carbon emissions in a flexible manner within the carbon market. With this assumption in mind, we are trying to find out whether it can contribute to the decarbonization of buildings and how building users will adjust their energy consumption behavior.

To tackle this issue, we have modified the Stochastic Dynamic Programming (SDP) framework to analyze the long-term economic effects of carbon trading on buildings. The objective is to minimize the operational costs of buildings. The comprehensive optimization model will be multi-objective, aiming to balance both electricity operational costs and the carbon costs incurred at the end of the year through the Emissions Trading Schemes (ETSs). Our key contributions are as follows:

1. By adding carbon costs to the SDP framework, we have redefined the optimal year-round operation strategy for buildings.
2. We looked at how different CO_2 prices affect a building's operational strategy throughout the year.

The rest of the paper is structured as follows: Section 2 outlines the model. Section 3 provides a detailed case study, and Section 4 presents the results along with a discussion. Finally, the conclusion is offered in Section 5.

2. MODEL DESCRIPTION

The building operates under an intelligent control system. Using this system, the end-user transitions to a more active role, adjusting their energy consumption based on fluctuating energy supplies or financial incentives. Considered that the building has two sources of electricity, one is from traditional power grid and the other renewable power is from the DESs. Due to the uncertainty and fluctuation in renewable generation over time, the energy purchase portfolio within the year becomes more important. The problem being modeled in the present study is to determine the best energy purchase combination to meet the residential user comfort and the energy demand of the building subject to practical constraints. The duration of this work is one year and includes the carbon trade which taking into account the cost of the $CO_{2eq\text{-}emissons}$ in the year.

2.1. Model overview

This research utilizes a long-term operational model for residential buildings to enhance the operational strategy of an electrified building over a planning period of one year. This study focuses on a one-year horizon, structured into weekly decision-making stages. At the beginning of each week, the stochastic variables are determined and remain constant throughout that week. The key stochastic variables considered in this research include outdoor temperature, solar irradiation, electricity prices, and load patterns specific to consumers.

Throughout the year, we modify the building's flexible load using the control system to regulate the weekly purchase volumes of two types of electricity from the grid. The quantities of electricity purchased have a direct effect on $\mathrm{CO}_{2eq\text{-emissions}}$, which must comply with or fall below the established carbon quota; otherwise, emission rights must be acquired to accommodate any additional carbon emissions. The objective for the year is to minimize the overall operating costs associated with electricity procurement from the grid, alongside the costs related to carbon emissions.

$$\min \mathbb{E}\left\{\sum_{t=1}^{8760}\left(e_t^{utility}\cdot P_t^{utility}+e_t^{micro}\cdot P_t^{micro}\right)+\Phi\left(e_{CO_{2eq}}\right)\right\} \tag{1}$$

The variable $\Phi\left(e_{CO_{2eq}}\right)$ denotes the expense related to the total emissions accumulated throughout the year. The carbon emissions variable $e_{CO_{2eq}}$ records the emissions associated with the electricity imported from the power grid. A negative $\Phi\left(e_{CO_{2eq}}\right)$ means that we have emitted less than the carbon quota limit and can sell the extra quotas, while a positive $\Phi\left(e_{CO_{2eq}}\right)$ implies that we need to buy carbon quotas on the market to reach a carbon balance at the end of the year. The cost function associated with carbon emissions is illustrated in Eq. (2), in which a carbon quota X is established to control the emissions.

$$\Phi\left(e_{CO_{2eq}}\right)=\left(e_{CO_{2eq}}/A-X\right)\cdot P^{CO_2} \tag{2}$$

2.2. Decomposed decision problem

2.4.1. Objective function

The goal of the objective function in this optimization problem is to reduce the overall energy expenses for the residential user, while considering the expected future costs of carbon transactions $\alpha^{future}_{e_{CO_{2eq}},n}$ related to the total accumulated $\mathrm{CO}_{2\mathrm{eq}}$ emissions at the conclusion of the period. This cost is consequently connected to the variable energy demand over time for real-time pricing (RTP), the $\mathrm{CO}_{2\mathrm{eq}}$ emission factors during the period, and the initial accumulated $\mathrm{CO}_{2\mathrm{eq}}$ emissions recorded at the start of the week.

$$\min\left\{\sum_{t\in\mathcal{T}}\left[e_t^{utility}\cdot p_t^{utility}+e_t^{micro}\cdot p_t^{micro}\right]+\alpha^{future}_{e_{CO_{2eq}},n}\right\} \tag{3}$$

2.4.2. Carbon trading and future cost

The constraints concerning carbon trading and the framework for the anticipated future carbon costs are provided in Eqs. (4a) and (4b). The $\mathrm{CO}_{2\mathrm{eq}}$ emissions accumulated for this stage are illustrated in Equation (4a), in which the total is derived from the previous stage and the aggregate of utility electricity consumption, factoring in the $\mathrm{CO}_{2\mathrm{eq}}$ emission rate for this stage. This accumulated total serves a critical role, as it is used to define the expected future cost variable $\alpha^{future}_{e_{CO_{2eq}},n}$ in Equation (4b).

$$e_{CO_{2eq},n}=e_{CO_{2eq},n-1}+\sum_{t\in\mathcal{T}}e_t^{utility}\cdot K_t^{elec} \tag{4a}$$

$$\alpha^{future}_{e_{CO_{2eq}},n}=\Phi\left(e_{CO_{2eq},n}\right) \tag{4b}$$

2.4.3. Energy balance

Eq. (5) illustrates the energy balance for the electrical system within the building. This balance incorporates electricity obtained from the utility grid and the microgrid, alongside the charging and discharging activities of the battery energy storage system. Furthermore, it includes the energy consumption associated with the lighting system, household appliances, space heating, and electric water heaters.

$$e_t^{utility} + e_t^{micro} + b_t^{dch} = l_t + a_t + q_t + h_t + b_t^{ch} \quad \forall t \tag{5}$$

2.4.4. Lighting system

The lighting system is defined in detail in Eq. (6). The lighting power consumption is proportional to the building area, the per unit area consumption assumed as constant, and it is hinged on the lighting use rate and occupancy rate at home as well.

$$l_t = l_0 \cdot A \cdot \delta_t^{light} \cdot \lambda_t \quad \forall t \tag{6}$$

2.4.5. Appliances

The primary source of the electricity utilized for appliances is refrigerators, microwave oven, electric boilers, washing machine, etc. Generally, it is calculated in a similar way to the lighting system, given by Eq. (7).

$$a_t = a_0 \cdot A \cdot \delta_t^{apps} \cdot \lambda_t \quad \forall t \tag{7}$$

2.4.6. Battery energy storage system

The building features a bi-directional stationary battery that can be managed according to Eqs. (8a) to (8d). This battery facilitates power flow in both directions at a constant rate, subject to limitations imposed by its power and storage capacities. The storage capacity is maintained within a specified range to ensure optimal performance while preventing any potential damage to the battery.

$$E_t^B - E_{t-1}^B = b_t^{ch} \cdot \eta^{ch} - \frac{b_t^{dch}}{\eta^{dch}} \quad \forall t \tag{8a}$$

$$0 \le b_t^{ch} \cdot \eta^{ch} \le \dot{E}^{B,ch} \quad \forall t \tag{8b}$$

$$0 \le b_t^{dch} \le \dot{E}^{B,dch} \quad \forall t \tag{8c}$$

$$E^{B,\min} \le E_t^B \le E^{B,\max} \quad \forall t \tag{8d}$$

For reasons of space, more constraints are not shown here.

3. CASE STUDY

The model is implemented in an electrified residential building in Chongqing, known as a green-electrified building (GEB). This innovative structure is equipped with a sophisticated smart control system that oversees flexible assets while simultaneously monitoring two distinct sources of electricity. The analysis is centered on the year 2019, employing an hourly time resolution over the course of 52 weeks, with historical data incorporated as stochastic variables to enhance the accuracy of the model. The GEB utilizes distributed energy systems (DESs) to supply renewable electricity to its residents, which not only fosters sustainability but also ensures the safety and stability of the overall power system.

3.1. Building structure

Building structure, energy prices, and equipment parameters refer to national and regional standards and survey data.

3.2 Scenario generation

The control system, alongside the Stochastic Dynamic Programming (SDP) algorithm, is designed to accommodate multiple uncertainties in input data throughout its operational phases. In order to effectively narrow down the range of uncertainties and enhance the functionality of the algorithm, this study specifically examines uncertainties arising from weather factors, particularly focusing on outdoor temperature and solar irradiation. Additionally, various aspects of building usage—such as occupancy rates, lighting consumption, appliance utilization, cooking times, and hot water usage—are treated as deterministic variables for the entire year. This research generates a total of three scenarios for each week, formulated based on a normal distribution of the weather-related variables. The normal distribution results in a probability of $\rho\mu$ = 68.2% and $\rho\sigma$ = 15.9% for the three scenarios considered. Furthermore, it is crucial to emphasize that the probability distribution for future scenario nodes remains constant, regardless of the conditions of the current operational scenario.

4. RESULT & DISCUSSION

This section outlines the findings from the case study and elaborates on the contributions and significance of these results. Table 1 displays the annual total costs incurred by the family in the Green Electrified Building (GEB), along with the corresponding carbon trading volumes for carbon prices ranging from 0 to 10 CNY/kgCO$_2$, while considering a carbon emission allowance of 3,500 kgCO$_2$.

The trend illustrated in Table 1 indicates that a rise in carbon pricing results in a reduction of both operating costs and the volume of carbon trading. The high carbon price has led to a reduction in carbon emissions by the control system to reduce flexible loads and shift to clean energy consumption. In the whole process, the carbon trading volume is always positive, indicating that no matter what strategy we adopt, the carbon emissions are greater than the carbon quotas, which means that our carbon quotas are set more strictly. Staring at 5 CNY/ kgCO$_2$, the operating cost is close to the lowest and the carbon trading volume is touching the bottom. After that, with the rise in carbon prices, the operating cost and the total cost remain largely unchanged. In practice, too high carbon prices may cause public dissatisfaction and refuse to participate in carbon trading. Therefore, a reasonable price, like 5 CNY/ kgCO$_2$, might be acceptable to the public.

Table 1. The total operating cost including/excluding the carbon cost, and the final carbon trading volume

Carbon price [CNY/kgCO$_2$]	**Operating cost [CNY]**	**Operating cost + Carbon cost [CNY]**	**Carbon trading volume [kgCO$_2$]**
0	3856.4	3856.4	494.6
1	3842.1	4263.3	421.2
2	3679.8	4400.6	360.4
3	3527.4	4092.0	188.2
4	3442.5	3602.9	40.1
5	3398.3	3407.3	1.8
6	3392.7	3396.3	0.60
7	3392.4	3396.3	0.56
8	3391.8	3395.6	0.48
9	3391.2	3395.1	0.43
10	3391.1	3395.3	0.42

5. CONCLUSION

This paper leverages the stochastic dynamic programming (SDP) framework to develop a model focused on the optimization of annual operational strategies, with an emphasis on the management of carbon emissions. The proposed model was implemented in a Chongqing green-electrified building during the year 2019 to find the cost-optimal strategy. This operational strategy provides a sensitivity analysis of carbon pricing. With an increasing carbon price, the total cost is decreasing, which is achieved by reducing flexible loads and shift to low-carbon electricity consumption. Carbon trading net zero point was achieved at 5 CNY/ $kgCO_2$ and above. When increasing the carbon price further, the cost almost remained unchanged. Taking into account the emotions and participation of the public, the best carbon price is 5 CNY/ $kgCO_2$. Future research can discuss the impact of carbon emission allowances on costs and strategies when carbon price does not work.

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