Energy flexibility analysis of office building using pre-cooling with structural thermal mass

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Abstract. The increasing share of renewable energy sources (RES) increases the imbalance between supply and demand, due to its fluctuation and intermittence. Energy flexible buildings are proposed as an important part of the solution to balance supply and demand. However, the thermal storage of a building is not utilized for reducing the considerable peak-to-valley difference in conventional night setup control strategies. In this context, pre-cooling is the most commonly used approach for charging cooling in building thermal mass to achieve energy flexibility. The objective of this paper is to assess the building flexibility potential using pre-cooling with structural thermal mass. We proposed quantitative indexes including valley-filling capacity, peak-shaving capacity and energy-shifting efficiency based on the improvement of existing indicators according to previous research. As considering the impact of structural thermal mass, heat transfer coefficient, pre-cooling duration, pre-cooling temperature on energy flexibility, a total of 35 scenarios are simulated using TRNSYS and evaluated using the quantitative indexes. Finally, the results may supply suggestions to utilize building energy flexibility with pre-cooling and optimize the corresponding control strategy.

1. Introduction

In many countries, the growing share of renewable energy sources (RES) goes with the extensive electricity demand[1]. In China, the proportion of renewable energy generation on the supply side has increased from 16% to 25% during recent 10 years. The increasing share of renewable energy sources (RES) brings up new challenges to supply-side due to its fluctuation and intermittence. These challenges include: increasing the imbalance between supply and demand, drastic loads variations over a day, more complex control problems. Flexible energy building are proposed as an important part of the solution to balance supply and demand. The IEA EBC proposes a comprehensive definition for energy flexibility: It is the ability to manage its demand and generation according to local climate condition, user need and grid requirement. Energy Flexibility of buildings will allow for demand side management and thereby demand response based on the requirements of the surrounding grids. However, there is a considerable peak-to-valley difference of office buildings. The thermal storage of a building is not utilized for reducing the difference in conventional night setup control strategy. Pre-cooling is the most commonly used approach for charging cooling in building thermal mass, which can achieve peak-shaving, valley-filling, load-shifting. Therefore, utilizing pre-cooling strategy with structural thermal is of great importance to attain much flexibility from demand-side.

The objective of this paper is to assess the building flexibility potential using pre-cooling with structural thermal mass. In a first part, the measured building electricity curve under conventional night setup control strategies in cooling season are analysed. In a second part, we proposed the quantitative indexes (valley-filling capacity, peak-shaving capacity, and energy-shifting ratio) based on the improvement of existing indicators. In a third part, parameter study is carried out to
quantify the impact of structural thermal mass, heat transfer coefficient, pre-cooling duration time and pre-cooling temperature on the energy flexibility. A total of 35 scenarios are simulated using TRNSYS and evaluated using quantitative indexes. Finally, the results may supply suggestions to utilize building energy flexibility with pre-cooling and optimize the corresponding control strategy.

2. Building energy characteristics under conventional control strategies
The measured building electricity curve under conventional night setup control strategies in cooling season are shown in Figure 1. Energy use for office building is fixed, and the Heating ventilation and air-conditioning (HVAC) system accounts for 67.1% of the total electric load in cooling season. However, there is a considerable peak-to-valley difference of HVAC electric load and the thermal storage of a building is not utilized for reducing the difference in conventional night setup control strategy.

Figure 1. Building electricity load curve (electricity load curve of two weeks (left) and typical daily electricity load curve (right))

Pre-cooling is commonly used for charging cooling in building thermal mass. Thermal energy storage using pre-cooling strategy can shift the energy demand to off-peak hours, aiming to achieve peak-shaving, valley-filling and load-shifting. Experimental study confirmed more than 30% daily peak load reduction in on-peak period. The energy flexibility obtained by pre-cooling depends on several parameters: level of insulation, level of thermal mass, pre-cooling duration time, pre-cooling temperature, type of emitter, etc. Nevertheless, few studies have quantified the influence of building and pre-cooling parameters on energy flexibility using pre-cooling with structural thermal mass.

3. Evaluation of building energy flexibility using thermal mass
Charging the structure thermal mass by pre-cooling during off-peak periods can be used to increase energy use during off-peak periods (valley filling), reduce the energy demand at peak period (peak shaving), and shift the energy demand from peak period to off-peak period (energy shifting). In order to quantify the increase in energy demand during the off-peak time, the valley-filling capacity \( Q_{valley-filling} \) is given by the integral of the difference between the cool input \( P_{pre-cooling} \) and the cool input in reference condition \( P_{ref} \) during pre-cooling period, as shown in equation 1, with \( t_{pre-cooling} \) the duration of the pre-cooling event.

\[
Q_{valley-filling} = \int_{0}^{t_{pre-cooling}} (P_{pre-cooling} - P_{ref}) dt
\]  (1)

To quantify the reduction in energy demand during on-peak periods, the peak-shaving capacity \( Q_{peak-shaving} \) is given by the integral of the difference between the cool input in reference
condition \( (P_{\text{ref}} \ [\text{W}]) \) and the cool input in pre-cooling condition \( (P_{\text{pre-cooling}} \ [\text{W}]) \) after pre-cooling activation, as shown in equation 2.

\[
Q_{\text{peak-shaving}} = \int_{t_{\text{pre-cooling}}}^{\infty} (P_{\text{ref}} - P_{\text{pre-cooling}}) \, dt
\]  

(2)

The energy-shifting ratio \( (\eta_{\text{energy-shifting}}) \) is defined as the fraction of the peak-shaving capacity to the valley-filling capacity, as shown in equation 3.

\[
\eta_{\text{load-shifting}} = \frac{Q_{\text{peak-shaving}}}{Q_{\text{valley-filling}}}
\]  

(3)

4. Description of case study

4.1. Multi-zone building description

The parameter study is carried out on a multi-zone building, as shown in Figure 2. The office building with four floors and a total area of 4025m\(^2\) in Beijing is chosen as a benchmark building. Additionally, the composition of building envelope in the benchmark building are listed in Table 1. Since the third floor is equipped with ground source heat pump system and radiant emitters (chilled-ceiling) independently, this paper takes the third floor as an example to study the building cooling power flexibility. The third floor is consist of office rooms and meeting rooms. Considering the actual situation of nearly zero energy office building, the internal heat gain mainly includes person, lighting and office equipment. The occupant density is 10m\(^2\)/person, the metabolic rate is 120 W/person, and the radiative heat transfer ratio is 40%. The building uses LED lighting with power density of 5 W/m\(^2\) and a radiative heat transfer ratio of 70%. The power density of office equipment is 11W/m\(^2\), and the radiative heat transfer ratio is 30%. Building air tightness is set 0.6h\(^{-1}\) under 50 pa.

![Figure 2. Schematic diagram of floor plan for the office building](image)

Table 1. Selected parameters and range of values

| Building component type | Composition | U-value (W/m\(^2\)K) |
|------------------------|-------------|----------------------|
| **External wall**      | 20mm cement mortar+22mm STP insulation+200mm air-entrainment concrete block+20mm cement mortar | 0.24 |
| **Internal wall**      | 20mm cement mortar+200mm air-entrainment concrete block+20mm cement mortar | 1.28 |
| **Ceiling**            | 20mm plasterboard+150mm reinforced concrete+20mm cement mortar | 2.96 |
| **Floor**              | 20mm cement mortar+150mm reinforced concrete+20mm plasterboard | 2.96 |

4.2 Scenarios of pre-cooling

The parameters have been selected to allow an evaluation of the impact of the envelope performance level, the structure thermal mass, the pre-cooling temperature as well as the pre-cooling duration time,
as shown in Table 2. The exterior walls are modelled as aerated concrete brick wall and clay brick wall, representing light and heavy exterior wall respectively. Note that, aerated concrete brick wall is a common construction of new building, while clay brick wall is commonly used for 80’s building. Two different building envelope thermal performance are considered according to the recommendations of national standard. Different pre-cooling time and temperature have been considered. Detailed building and system physics model is built in TRNSYS, as it is a widely validated Building Energy Simulation tool. The control of the cooling set-point is handled by a PID controller. As considering the above parameters, a total of 35 scenarios are generated. A reference case (constant cooling set-point of $26^\circ C$) is also conducted as benchmark building.

### Table 2. Selected parameters and range of values

| Parameter                                      | Range of values |
|-----------------------------------------------|-----------------|
| Exterior wall thermal mass (kg/m²K)           | 202.6, 557.2    |
| Exterior wall heat transfer coefficient (W/m²K)| 0.24, 0.63      |
| Duration of ADR event (h)                     | 2, 3, 4, 5, 6, 7, 8 |
| ADR temperature (°C)                          | 23, 24, 25      |
| ADR comfort range (°C)                        | 2               |

### 5. Results and discussion

In this paper, the average value of simulation results under 35 scenarios during July is figured out and analyzed in the following part.

#### 5.1. Impact of pre-cooling temperature and time on building energy flexibility

Firstly, the pre-cooling time has a significant influence on energy flexibility. The energy-shifting ratio decreases with increasing pre-cooling time, while the valley-filling capacity and peak-shaving capacity increases with increasing pre-cooling time. Long-time pre-cooling is recommended from the perspective of a higher valley-filling capacity and peak-shaving capacity, whereas short-time pre-cooling is recommended to achieve a higher energy-shifting ratio. Secondly, two important trends are found for the influence of pre-cooling temperature on flexibility. Valley-filling capacity, peak-shaving capacity all increase with a lower pre-cooling temperature. Nevertheless, a higher energy-shifting ratio can be obtained under high pre-cooling temperature. Besides, a significant spread of energy-shifting ratio is shown, values above 0.5 are obtained for all cases.

#### 5.2. Impact of exterior wall heat transfer coefficient on building energy flexibility

As can be seen from Figure 4, the valley-filling capacity is higher for the low-insulation cases. However, a higher peak-shaving capacity and energy-shifting ratio are found for high-insulation
building. As such, an optimum insulation level may be expected to achieve a balance between a high valley-filling capacity and an acceptable energy-shifting ratio.

Figure 4. Valley-filling capacity (left), peak-shaving capacity (middle), energy-shifting ratio (right) as a function of exterior wall heat transfer coefficient

5.3. Impact of exterior wall thermal mass on building energy flexibility

No significant difference is observed for buildings with light and heavy thermal mass in terms of valley-filling capacity. The impact of the exterior wall thermal mass on peak-shaving capacity and energy-shifting efficiency is more pronounced compared with on valley-filling capacity. It is worth noting that pre-cooling duration time and thermal mass have an interaction effect on flexibility. For example, heavy-weight building can achieve a higher peak-shaving and energy-shifting ratio under long pre-cooling time. Future research should pay more attention to the combined effect of thermal mass and pre-cooling time on energy flexibility.

6. Conclusion

Flexible energy building are proposed as an important part of the solution to balance supply and demand. Pre-cooling is a commonly used approach for charging cooling in building thermal mass to achieve energy flexibility. This paper assesses the building flexibility potential using pre-cooling with structural thermal mass considering exterior wall thermal mass, heat transfer coefficient, pre-cooling duration time and pre-cooling temperature. We also proposed the quantitative indexes based on the improvement of existing indicators. Detailed building and system physics model is built in TRNSYS with a total of 35 scenarios simulated. The simulation results are evaluated in terms of valley-filling capacity, peak-shaving capacity and energy-shifting ratio. The main conclusions are:
The pre-cooling duration time and pre-cooling temperature has a significant influence on energy flexibility, the envelope insulation level is second. However, the impact of the exterior wall thermal mass is less pronounced compared with other parameters.

- Low-insulation, low pre-cooling temperature, long-time pre-cooling and heavy-weight wall are recommended for a high valley-filling capacity.
- High-insulation, low pre-cooling temperature, heavy-weight wall and optimized pre-cooling duration time is suggested to achieve high peak-shaving capacity.
- In order to guarantee high energy-shifting ratio, short pre-cooling time, higher pre-cooling temperature and high-level insulation is recommended.
- Further study may be expected for insulation level optimum whereby a balance is found between a high valley-filling capacity and an acceptable energy-shifting ratio.
- It is worth noting that pre-cooling duration time and thermal mass have an interaction effect on building flexibility. Future research should pay more attention to the combined effects of thermal mass and pre-cooling time on energy flexibility.

Finally, the results may supply suggestions to utilize building energy flexibility with pre-cooling and optimize the corresponding control strategy.

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