Impact of building design and temperature setpoint control on energy flexibility performance.

Meysam Akbari Paydar[1*], Craig Robertson[2], Dejan Mumovic[1], Esfand Burman[1]

[1] Institute for Environmental Design and Engineering, University College London, UK.
[2] Allford Hall Monaghan Morris, London, UK.

* Corresponding author meysam.paydar.22@ucl.ac.uk

Abstract. The integration of renewable energy sources into electricity grids has emphasized the need for demand-side management to enhance grid stability. Among various strategies, utilizing building thermal mass as a form of energy storage by adjusting indoor temperature setpoints presents a promising approach to improving energy flexibility. However, despite its significance, energy flexibility is often overlooked in the architectural design process, where regulations focus primarily on energy efficiency rather than the flexibility potential of building components. This study investigates the impact of different design parameters, including building design based on regulatory and Net Zero energy targets, varying levels of thermal mass, HVAC configurations, and setpoint control strategies on building energy flexibility. Simulations were conducted to assess performance across winter and summer periods. The findings reveal that Net Zero buildings exhibit lower flexibility in winter but greater adaptability in summer. VRF (DOAS) systems demonstrate superior flexibility in winter, whereas All-Air system (VAV) and Chilled Ceiling systems perform best in summer. Thermal mass influences energy flexibility more significantly in summer than in winter, with optimal levels varying by HVAC system and control strategy. The results underscore the importance of integrating energy flexibility considerations into early-stage design decisions to enhance building performance in energy flexibility.

1. Introduction

The integration of renewable energy into electricity grids has heightened the importance of demand-side management for grid stability. Given the variability of renewable generation, buildings must adjust their energy consumption to align better with available renewable supplies. Energy flexibility can be improved through methods like battery storage, thermal energy storage tanks, and utilizing a building's thermal mass, which can be charged and discharged by adjusting indoor temperature setpoints [1]. As this approach depends on building components, it is essential to incorporate energy flexibility into the architectural design process. However, it is often overlooked during the design phase, where standards focus primarily on energy performance metrics. Therefore, it is necessary to investigate how control strategies for indoor temperature setpoints and specific building characteristics affect energy flexibility.

Several studies have examined the role of building thermal mass in energy flexibility [2, 3]. Lu et al. [4] found that its effectiveness in a nearly zero-energy office in Beijing depends on structural thermal capacity, internal heat gains, and cooling system type, with external wall insulation having little effect. Liu and Heiselberg [5] showed that combining energy price and weather prediction for setpoint control in Copenhagen can shift up to 80% of energy consumption during high-price periods, although total costs increased slightly. Dreau and Heiselberg [6] studied how building characteristics influence thermal mass use for shifting heating demand in Danish homes. They tested two strategies, raising and lowering setpoints, under varying insulation levels and heating systems, finding that poorly insulated buildings allow short-term modulation (2–5 hours), while passive houses enable extended modulation (over 24 hours) due to higher thermal inertia. Ruan et al. [7] demonstrated that preheating, especially at 25°C, enhances energy flexibility during the heating season in a residential building in Japan.

Although previous studies offer valuable insights into thermal mass's role in energy flexibility, a comprehensive understanding of how various building design parameters influence energy flexibility is still lacking. Factors such as construction characteristics, HVAC systems, heating and cooling terminals, occupant comfort, climate, and seasonal variations need to be examined together. This study aims to fill this gap by analyzing energy flexibility across design parameters, including regulatory and Net Zero energy design targets, thermal mass levels, HVAC configurations, and setpoint control strategies. The results will be evaluated separately for winter and summer to better understand how these factors affect energy flexibility in heating and cooling seasons.

2. Methodology

This section outlines the simulation-based method for assessing building energy flexibility.

2.1. Peak period

Various metrics have been used to define peak periods for analysing building energy flexibility, such as grid peak hours [8], electricity tariffs [9], and carbon intensity levels [10]. Since this study focuses on the design stage and future operation—when tariffs and carbon intensity may change due to increased renewable energy—a general approach is adopted to assess how design scenarios affect energy flexibility. In the UK, historical grid data show that daily demand patterns and peak hours have remained stable and are expected to continue (Figure 1). Thus, the peak period is defined as 7:00 AM to 7:00 PM, based on historical grid demand patterns and adjusted for typical office occupancy schedules. These hours generally coincide with high electricity demand and are likely to align with periods of higher carbon intensity and energy prices.

2.2. Flexibility temperature setpoint control

The reference setpoint temperature control strategy in this study follows the setpoint schedule defined for office buildings in the UK's National Calculation Methodology (NCM) [11]. This schedule includes a setback temperature that shifts to the occupancy setpoint two hours before occupancy begins, ensuring comfortable indoor conditions upon arrival. Enhancing energy flexibility involves modifying this setpoint (setpoint offset) and extending the preheating or precooling period (charging period) to store more thermal energy in the building's thermal mass (Figure 2).

According to CIBSE Guide A, the daily mean operative temperature should remain within a defined comfort range, and variations within ±1K are typically imperceptible to occupants [12]. Based on this, operative temperature is used as the control variable in this study, with its offset limited to ±1K. While adjustments mainly occur during unoccupied hours, excessive shifts may extend into occupied periods and affect comfort.

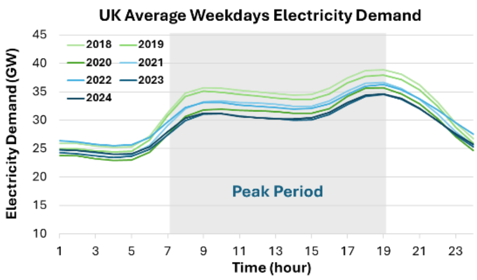


Figure 1. UK average weekdays electricity demand [13].

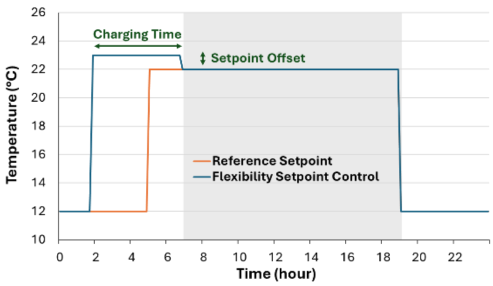


Figure 2. Energy flexibility temperature setpoint control strategy (winter).

2.3. Energy flexibility assessment method

Various quantitative indicators assess building energy flexibility, each offering unique insights [14]. However, for design-stage evaluation, metrics must enable comparison between thermal mass storage and alternatives like thermal storage tanks. Thus, this study uses two key metrics:

2.3.1. Heating/Cooling peak demand shift efficiency. This metric represents the proportion of the energy demand reduction during peak hours relative to the energy demand change during off-peak hours under flexibility control, compared to a reference scenario. In other words, it quantifies how much of the additional energy input during off-peak hours is effectively used to reduce demand during peak periods.

$$\eta_{H\ or\ C} = \frac{\int_{t_1}^{t_2} \left(P_{reference,t} - P_{flexible,t}\right) dt}{\int_{t_0}^{t_1} \left(P_{flexible,t} - P_{reference,t}\right) dt} \tag{1}$$

Where $P_{flexible,t}$ and $P_{reference,t}$ represent the total power of the heating or cooling system at time t under energy flexibility control and the reference case, respectively. This power includes the power of the heating or cooling sources and related auxiliaries (pumps, fans). t_0 is the charging start time, t_1 is the charging end and peak start time, and t_2 is the peak end time.

2.3.2. Heating/Cooling peak demand shift. This metric measures the percentage reduction in peak energy demand under flexibility control relative to a reference scenario.

$$\lambda_{H\ or\ C} = \frac{\int_{t_1}^{t_2} \left(P_{reference,t} - P_{flexible,t}\right) dt}{\int_{t_1}^{t_2} P_{reference,t}\, dt} \tag{2}$$

2.4. Simulation process

A dynamic simulation using EnergyPlus [15] was conducted to assess how building design and energy systems affect energy flexibility, supported by an automated Python workflow for model generation, simulation, and result processing (Figure 3). To validate the process, two methods were used. First, input data was modified according to ASHRAE 140 test cases (AE401 and AE403) [16] These test cases are part of a standardised method for validating building energy simulation tools. Both involve a VAV system with a reheat coil, similar to one of the systems considered in this study, and assess heating and cooling performance. The simulation results were then compared to the reference values provided by the standard and showed good consistency, demonstrating the reliability of the automated modelling process. Second, time-step outputs were generated and analyzed to verify the correct operation of different control strategies. For instance, checking setpoint outputs to ensure Energy Management System (EMS) functionality under varying flexibility strategies.

The study focuses on an office building in London, analyzing a mid-level floor with perimeter and core zones. Building geometry and input data are provided in Table 1. Simulations were conducted to assess energy flexibility across three building design targets: Part L (minimum regulatory requirement) [17], Net Zero (stretch scenario) [18], and an intermediate scenario. Various thermal mass levels and HVAC systems were also considered as variables (Table 2).

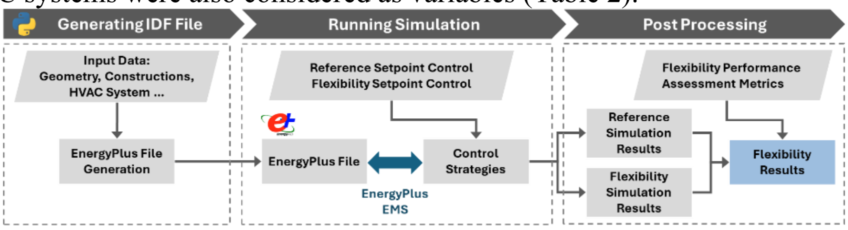


Figure 3. Automated simulation process.

Table 1. Properties of the building

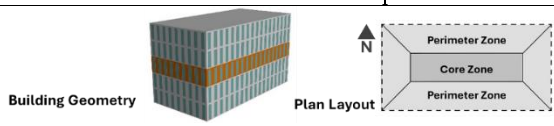
Parameter	Input
Building geometry and layout	
Heating/Cooling setpoint	22/24 °C (operative temperature) with setback
Number of people	0.111 person/m^2 - Occupancy period (Weekdays 7:00 to 19:00)
Lighting Level/power density	300 lux/1.5 (W/m^2-100 lux) with daylight control
Equipment power density	8 (W/m^2)
Mechanical ventilation rate	Demand Control Ventilation (DCV)/CO2 threshold = 1000 ppm
Heating COP/Cooling EER	2.8/5.5
Window Wall Ratio	0.4 - Glazing SHGC/Visible Transmittance (0.4/0.6)

Table 2. Building parameter variations.

Parameter		Variation Range		
Design Target		Part L	Intermediate	Net Zero
	External wall U-Value (W/m^2K)[a]	0.26	0.19	0.12
	Windows U-Value (W/m^2K)	1.6	1.3	1
	Infiltration rate ($m^3/h/m^2$ at 50 Pa)	8	4	1
Thermal Mass	Thermal mass ($KJ/m^2_{floor}.K$)[b]	100 – 1050		
HVAC System	All-Air System (VAV), Fan Coil-Dedicated Outdoor Air System (DOAS), VRF (DOAS), Radiator-Chilled TABS (DOAS), Radiator-Chilled Ceiling (DOAS)			
Flexibility Setpoint Control	Setpoint temperature offset	0, ±1 °C		
	Charging period	2, 3, 4, 5, 6 hours		
	Flexibility setpoint control periods	Winter: December, January, February Summer: June, July, August		

[a] The external wall U-value is adjusted by modifying the thickness of the insulation layer.
[b] The building's thermal mass is calculated based on the material layers located inside the insulation layer or air gap, considering only these as effective thermal mass layers. The thermal mass is varied by modifying the construction layers, including changes in layer types, thicknesses, and material properties.

3. Results and discussion

To evaluate the impact of design parameters and control strategies on energy flexibility, 720 simulations were run. This section presents the results for winter and summer separately.

3.1. Impact of building design target on energy flexibility

Figure 4 shows scatter plots of peak demand shift vs. shift efficiency for winter and summer, with design targets differentiated by colour. In winter, Part L-compliant buildings show greater flexibility, while in summer, Net Zero buildings perform better. The Intermediate Scenario ranks between the two in both seasons. To understand the Net Zero building's lower energy flexibility performance in winter, a detailed comparison was made with a Part L-compliant building on a specific winter day. A zone served by a Variable Refrigerant Flow (VRF) and Dedicated Outdoor Air System (DOAS) was selected to capture both zone-level heating demand and Air Handling Unit (AHU) heating requirements. As shown in Figure 5, the Part L building exhibits near-zero AHU heating demand throughout the day. This results from higher infiltration rates reducing fresh air needs, allowing heat recovery and return air mixing to maintain supply air temperature without additional heating. Additionally, extending the thermal mass charging period effectively lowers VRF heating demand during peak hours. In contrast, the Net Zero building's airtight envelope minimizes heat loss, and internal gains are sufficient to maintain indoor temperatures during peak hours, limiting the benefit of preheating. However, its higher fresh air demand leads to significant AHU heating during peak hours, even when operative temperatures exceed the setpoint. Because thermal mass primarily influences zone-level heat storage and release, it does not directly reduce heating needs at the AHU level. This limits energy flexibility related to AHU heating and explains the Net Zero building's poorer winter energy flexibility performance.

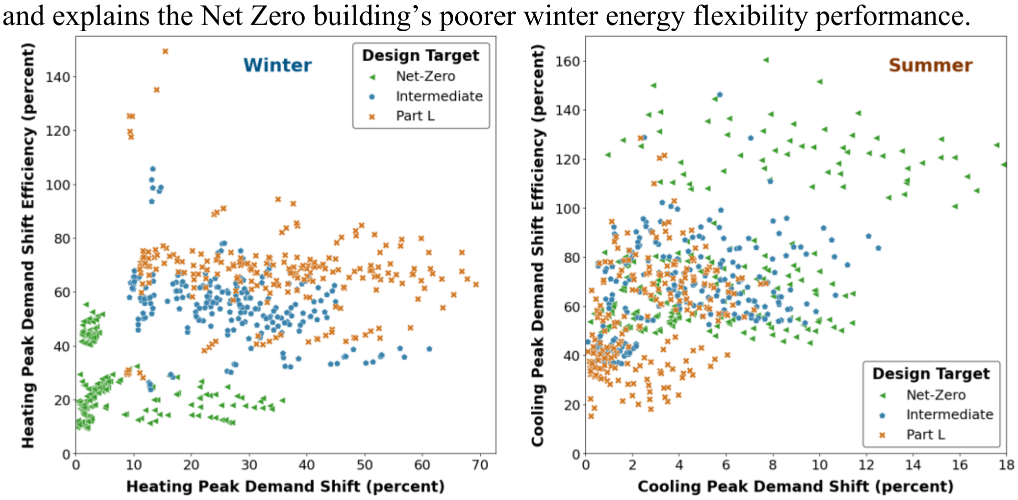


Figure 4. Impact of building design target on energy flexibility metrics in winter and summer.

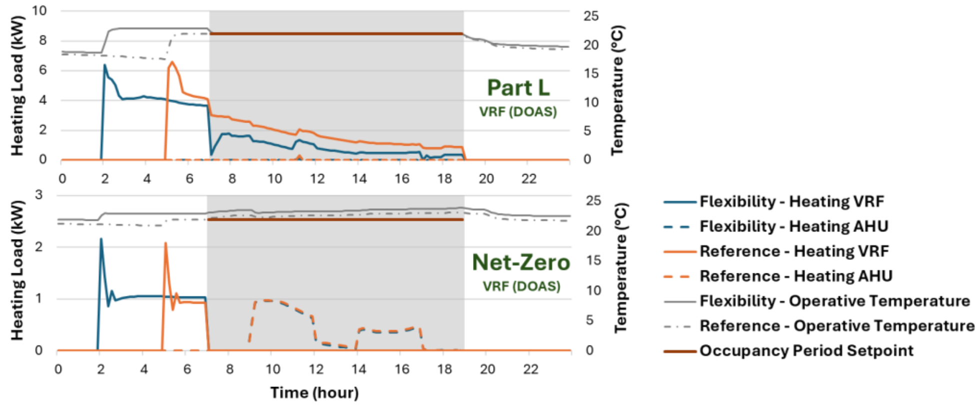


Figure 5. Comparison of the heating load of a zone on a winter day for the Part L and Net Zero buildings.

3.2. Impact of HVAC systems and heating/cooling terminals on energy flexibility

Figure 6 shows the impact of HVAC system types on energy flexibility. In winter, the VRF (DOAS) system delivers the highest demand shift and efficiency due to its low auxiliary energy use, while the All-Air system performs the worst because of its high auxiliary demand. In summer, however, the All-Air system performs comparably to the Chilled Ceiling system, showing better energy flexibility.

To explain this, a detailed comparison was made between the All-Air and VRF (DOAS) systems on a summer day (Figure 7). During the night charging period, the All-Air system maintains near-zero cooling load, except when outdoor temperatures exceed 14°C (the AHU setpoint), by supplying large volumes of cool outdoor air to the zone. In contrast, the VRF (DOAS) system requires mechanical cooling even at night, as its lower outdoor air supply capacity is insufficient to reach setpoint temperatures, even at full operation. Therefore, the All-Air system achieves higher summer flexibility due to its superior free cooling capability.

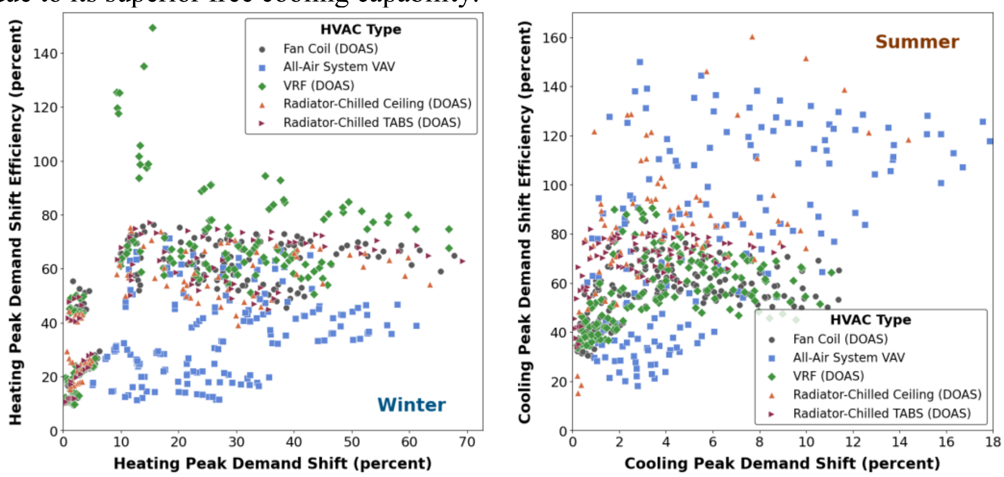


Figure 6. Impact of HVAC systems on energy flexibility metrics in winter and summer.

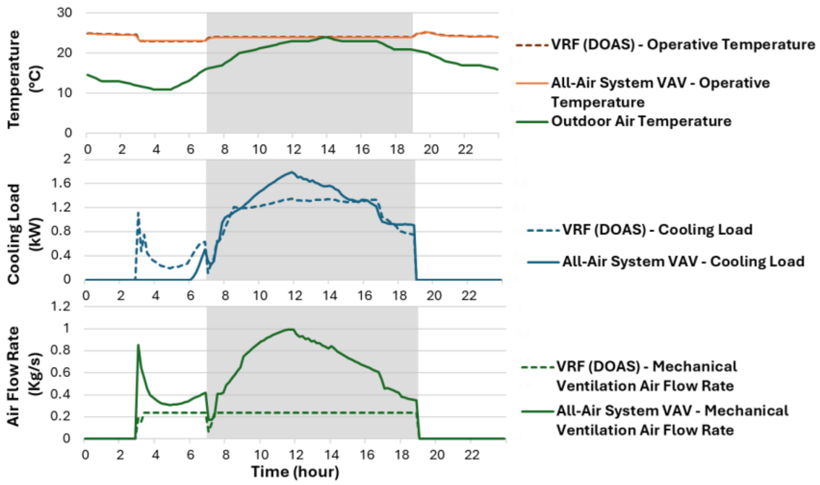


Figure 7. Comparison of the cooling load and mechanical ventilation rate of a zone on a summer day for the building with All-Air and VRF systems.

3.3. Impact of building thermal mass on energy flexibility

Figure 8 shows how thermal mass affects energy flexibility in a building with an intermediate design and various HVAC systems. Results indicate that summer flexibility is more sensitive to thermal mass changes than winter. In summer, moderate thermal mass (~300) yields high flexibility across most systems, except the All-Air system, which performs better with higher thermal mass due to its ability to store more free cooling without added demand. In winter, the influence of thermal mass is less significant, with only minor performance differences. Some systems benefit from higher thermal mass, while others perform better with moderate levels. These effects also depend on the building design target, suggesting that thermal mass should be considered in alignment with the building's envelope design. Overall, increasing the charging duration boosts peak demand shift but lowers shift efficiency. The degree of this trade-off varies by HVAC type, underlining the need to tailor setpoint control strategies to both the HVAC system and building design for optimal flexibility.

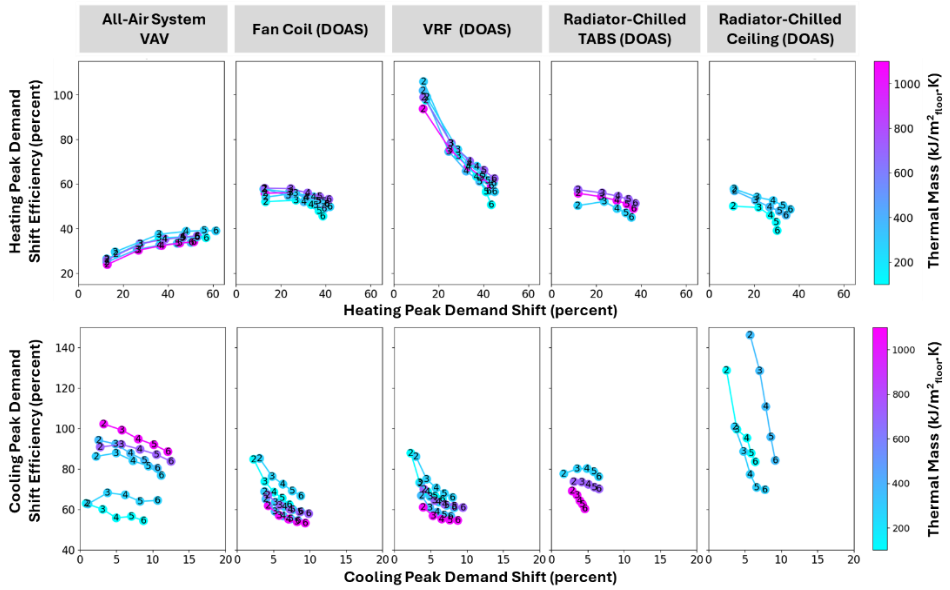


Figure 8. Impact of building thermal mass on the energy flexibility metrics for the building with intermediate design target, different HVAC systems, and various charging hours (temperature offset = ±1 °C).

4. Conclusion

This study investigated the potential of utilizing building thermal mass for energy flexibility through indoor setpoint control. Different building design targets—including minimum regulatory requirements (Part L), Net Zero, and an intermediate scenario—were analyzed alongside various HVAC systems, thermal mass levels, and setpoint control strategies. The results highlight that the correlation between building design and energy flexibility should be carefully considered during the design process to achieve high performance. Transitioning from a Part L-compliant building to a Net Zero building reduces energy flexibility performance in winter but enhances it in summer. Regarding HVAC systems, VRF (DOAS) systems achieve the highest flexibility performance in winter, while the All-Air system (VAV) performs the worst. In summer, the All-Air system (VAV) and Chilled Ceiling systems demonstrate the best energy flexibility. Building thermal mass has a greater impact on energy flexibility in summer than in winter, with the optimal thermal mass level depending on the HVAC system, building design target, and setpoint control strategy. Further research is needed to explore additional design parameters, such as building geometry, window-to-wall ratio, and internal gains, to fully understand their impact on energy flexibility.

Acknowledgments

This research was made possible by support from the EPSRC Centre for Doctoral Training in Energy Resilience and the Built Environment, grant number EP/S021671/1, and with financial support from [EPSRC + UCL ISAD + AHMM].

References

1. Jensen, S.Ø., et al., *IEA EBC Annex 67 Energy Flexible Buildings.* Energy and Buildings, 2017. **155**: p. 25-34.
2. Lind, J., et al., *Energy flexibility using the thermal mass of residential buildings.* Energy and Buildings, 2023. **301**.
3. Tang, H., S. Wang, and H. Li, *Flexibility categorization, sources, capabilities and technologies for energy-flexible and grid-responsive buildings: State-of-the-art and future perspective.* Energy, 2021. **219**.
4. Lu, F., et al., *Cooling system energy flexibility of a nearly zero-energy office building using building thermal mass: Potential evaluation and parametric analysis.* Energy and Buildings, 2021. **236**.
5. Liu, M. and P. Heiselberg, *Energy flexibility of a nearly zero-energy building with weather predictive control on a convective building energy system and evaluated with different metrics.* Applied Energy, 2019. **233-234**: p. 764-775.
6. Le Dréau, J. and P. Heiselberg, *Energy flexibility of residential buildings using short term heat storage in the thermal mass.* Energy, 2016. **111**: p. 991-1002.
7. Ruan, Y., et al., *Potential quantification and impact factors analysis of energy flexibility in residential buildings with preheating control strategies.* Journal of Building Engineering, 2023. **78**.
8. Arteconi, A., N.J. Hewitt, and F. Polonara, *Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems.* Applied Thermal Engineering, 2013. **51**(1-2): p. 155-165.
9. Reber, J., X. Kirschstein, and N. Bishara, *Evaluation of Building Mass Characterization for Energy Flexibility through Rule- and Schedule-Based Control: A Statistical Approach.* Energies, 2023. **16**(19).
10. Vigna, I., R. Lollini, and R. Pernetti, *Assessing the energy flexibility of building clusters under different forcing factors.* Journal of Building Engineering, 2021. **44**.
11. *National Calculation Methodology (NCM) Modelling Guide (for Buildings other than Dwellings in England)*. 2021.
12. (CIBSE), C.I.o.B.S.E., *Environmental design: CIBSE guide A*. 2021.
13. *The United Kingdom's electricity grid data*. 2025: https://gridwatch.templar.co.uk/.
14. Lu, F., et al., *Energy flexibility assessment of a zero-energy office building with building thermal mass in short-term demand-side management.* Journal of Building Engineering, 2022. **50**.
15. Crawley, D.B., et al., *EnergyPlus: creating a new-generation building energy simulation program.* Energy and buildings, 2001. **33**(4): p. 319-331.
16. ASHRAE, *ASHRAE Standard 140: Method of Test for Evaluating Building Performance Simulation Software*. 2022.
17. *Approved Document L, Conservation of fuel and power, Volume 2: Buildings other than dwellings*. 2021, Ministry of Housing, Communities and Local Government: London (UK).
18. (LETI), L.E.T.I., *LETI Climate Emergency Design Guide*. 2020: London (UK).