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EVALUATION OF ENERGY FLEXIBILITY POTENTIAL OF A TYPICAL THERMAL ZONE IN DUBAI

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ABSTRACT

With increased worldwide adoption of renewables, such as wind and solar, power grids face challenges with the inherent variability in renewables production. Energy flexibility is an essential part of the holistic solution toward this variable production. Buildings are the largest consumers of energy around the globe. However, they also have the ability to become energy flexible. This article investigates the potential energy flexibility of a building zone with typical thermal properties in compliance with the Dubai building code, located in Dubai, where the dominant energy load is cooling. The cooling load is provided through a convective air conditioning system, which is typical in Dubai, and the control strategy is based on the zone air temperature setpoint. Modulating the zone air temperature can result in significant changes in the cooling load, thus providing a certain amount of energy flexibility through the building thermal mass, which can then be used to shift and reduce the peak demand. We evaluated the effect of three strategies on the thermal zone, utilizing two energy flexibility indicators, the available structural energy storage capacity (C_{ADR}) and the storage efficiency (η_{ADR}). It is found that on a typical day in July, the analyzed zone can reach up to 570 Wh/m^2 of flexibility and achieve up to 3 h of load shifting, depending on the strategy utilized.

Keywords: convective cooling, demand response, energy flexibility, grid-interactive, peak demand, thermal mass.

1 INTRODUCTION

The worldwide electricity demand is expected to double by 2050 [1], and the electricity demand in the building sector is projected to increase by 70% [2]. The adoption and integration of renewable energy sources (RES) have increased at an accelerated pace due to recent global efforts to reduce greenhouse gas emissions. Total cumulative installed capacity for PV at the end of 2020 reached 767 GW, with 145 GW of PV installed in 2020 only [3], and the total global installed capacity for wind reached 743 GW, with 93 GW installed in 2020 [4]. In Dubai, the continuous increasement in electricity demand requires investment in developing more efficient and enhanced future energy networks. Peak demand is critical for the utilities as it defines the generation capacity requirements and, therefore, capital expenditure. In 2020, Dubai's peak load increased by 6.6% compared to 2019, which is equivalent to 558 MW (https://www.dewa.gov.ae/en/about-us/media-publications/latest-news/2020/08/dewa-records-a-peak-load). In Dubai, buildings are major energy consumers accounting for 80% of electricity consumption [5]. As their share is expected to grow due to urbanization, implementing new regulations and strategies to increase their offered flexibility to the grid will be very promising. On the other hand, with Shams Dubai, Dubai Electricity and Water Authority (DEWA) distribute generation program, impulse the transformation of the buildings into prosumers and contributors to electricity generation. With Dubai's vision of reaching 100% clean energy production by 2050, the challenge of integrating variable power resources is prominent as it can have severe effects on the stability of the energy system. Therefore, it is essential to balance the demand and supply and study the possibilities of a more flexible and

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adaptable grid. In many countries, energy flexible buildings are an integral part of the holistic approach in dealing with upcoming challenges due to the increased generation share from renewables.

Structural thermal storage (STES) is often suggested as a low-cost key technology to mitigate potential production and distribution capacity issues and improve the penetration of RES. Therefore, a quantitative assessment of the energy flexibility provided by structural thermal energy storage is essential to the large-scale deployment of thermal mass as the active storage technology in an active demand response (ADR) context. The available storage capacity expresses the amount of energy that can be added to the STES during a specific ADR event. Thus, the amount of cooling that can be stored within a thermal zone not only depends upon the thermal properties of the building fabric but also on the properties and actual use of the heating and ventilation systems [6]. The flexibility is measured compared to a reference and business-as-usual or baseline profile. Therefore, it is a relative concept that depends on a series of factors, including the range of the temperature change.

High temperatures characterize the United Arabic Emirates (UAE) weather for almost the whole year. Air conditioning represents 70% of the UAE's electricity use during the summer months, and it is the main reason for the daily peak demand. Figure 1 shows the typical shape of the demand profile in Dubai for July. The Emirate peak demand period falls between hours 12 and 18, the day's hottest hours.

On the other hand, buildings in the UAE are mainly constructed using high thermal mass elements like concrete structures and concrete blocks. That brings the opportunity to utilize the buildings' thermal mass to reduce the peak demand, enabling the utility to manage the load profile much easier and, over the long term, lowering aggregate system capacity requirements. The idea is to pre-cool the buildings' thermal mass and decrease the air conditioning system setpoint for some degrees during a specific time before the peak demand period. Then, the thermal energy stored in the construction elements can be released in the peak period, reducing the air conditioning needs and the peak demand.

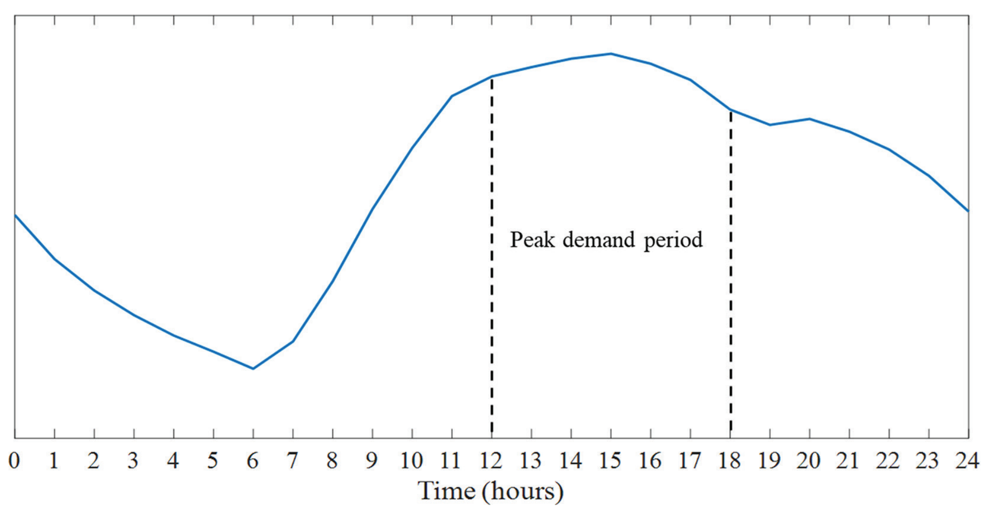

Figure 1: General trend of a typical July demand profile in Dubai.

The pre-cooling and the thermal energy discharge can be carried out without jeopardizing the occupants' thermal comfort. Therefore, this article aims to investigate the energy flexibility offered by the thermal mass of a building zone in Dubai with an air-based cooling system, evaluating and quantifying its peak shifting and load reduction potential for each proposed strategy.

In the following sections, we will introduce the flexibility indicators, explain the methodology, discuss the results and findings, and present the conclusions of our research work.

2 FLEXIBILITY INDICATORS

Four performance indicators or characteristics for ADR were developed by Reynders et al., [7] under the research tasks of the IEA annex 67, Energy Flexible Buildings [8]. These indicators include available structural energy storage capacity (C_{ADR}), storage efficiency (η_{ADR}), power shifting capacity (Q_{δ}), and state of charge (SOC). Figure 2 illustrates the concept for these indicators presented below. The structural energy storage capacity (C_{ADR}) and storage efficiency (η_{ADR}) are the indicators utilized in this article to quantify the energy flexibility potential of the building thermal mass.

The available structural energy storage capacity (C_{ADR}) is defined as the amount of cooling that can be added to the structural mass of a building for ADR event without jeopardizing indoor thermal comfort in a specific time frame (i.e. cooling above the upper threshold comfort temperature), which can be quantified as follows:

$$C_{ADR} = \int_{0}^{l_{ADR}} (Q_{ADR} - Q_{Ref})\, dt \, . \tag{1}$$

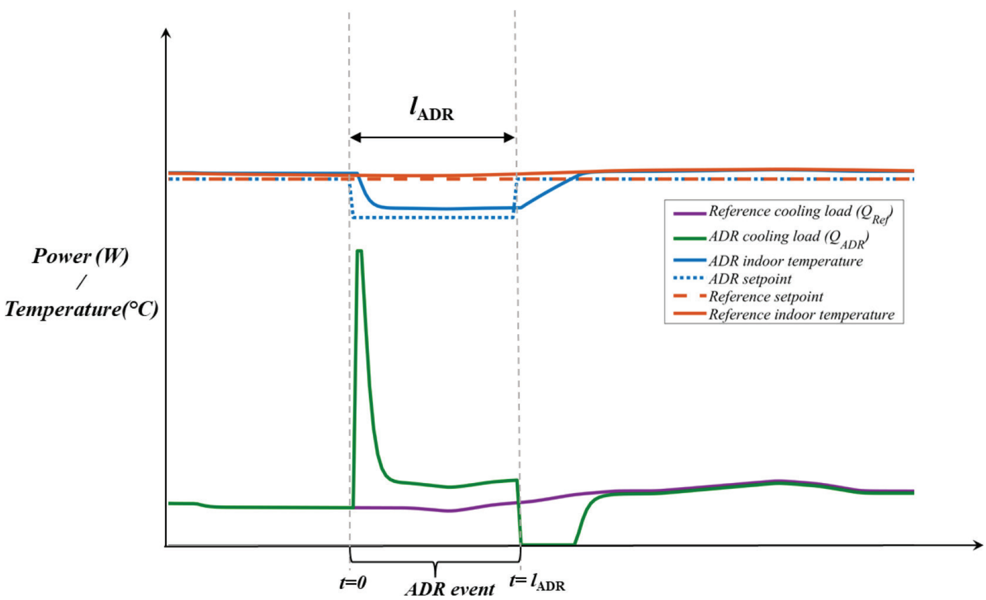

Figure 2: Conceptual representation of the measures used to quantify the available storage capacity.

The storage efficiency (η_{ADR}) represents the fraction of the heat that is stored during the ADR event that can be used subsequently to reduce the heating power needed to maintain thermal comfort.

$$\eta_{ADR} = 1 - \frac{\int_0^{\infty} (Q_{ADR} - Q_{\mathrm{Ref}})\, dt}{\int_0^{t_{ADR}} (Q_{ADR} - Q_{\mathrm{Ref}})\, dt} . \tag{2}$$

The power shifting capacity is the relation between the change in heating power (Q_δ) and the duration (t_δ) that this shift can be maintained before the normal operation of the system, i.e. thermal comfort is jeopardized:

$$Q_\delta = Q_{ADR} - Q_{\mathrm{Ref}} . \tag{3}$$

The more energy is stored within the building's thermal mass, the longer duration to reduce the heating power can be obtained. The state of charge (*SOC*) is used to explain the fraction of stored energy at time *t* compared to the total storage capacity:

$$SOC = \frac{E_{th}(t) - E_{th,\min}(t)}{E_{th,\max}(t) - E_{th,\min}(t)} . \tag{4}$$

3 METHODOLOGY

To investigate the contribution of the thermal mass to the potential of the energy flexibility of the buildings in Dubai, a gray-box thermal model was developed for a single building zone that considered the construction elements' characteristics of all the thermal flow and loads. The model was used to analyze the available structural energy storage capacity (C_{ADR}) and the storage efficiency (η_{ADR}) of office space in Dubai during summer conditions. For the analysis, the following three strategies are implemented:

- Lowering the air conditioning setpoint by 2°C (for 4 h)
- Lowering the air conditioning setpoint by 4°C (for 4 h)
- Ramp setpoint reduction of 4°C (for 4 h)

The following sections explain the weather conditions on a typical summer day, define the thermal model, and describe the office zone studied.

3.1 Dubai climate and a July typical day

As per DOE/ASHRAE Building Climate Zone, Dubai is classified as 0B (extremely hot) with an annual cooling degree-days CDD10.0 equal to 6,720 and a cooling degree-hours CDH23.3 equal to 51,416. This explains the relevance of reducing the cooling load, specially, during the peak demand periods. To obtain the initial findings on the potential energy flexibility provided by the thermal mass, this study is focused on a typical day in July. Figures 3 and 4 show the dry bulb temperature and the solar radiation of this summer day generated using an EnergyPlus EPW weather file provided by the US DOE [9].

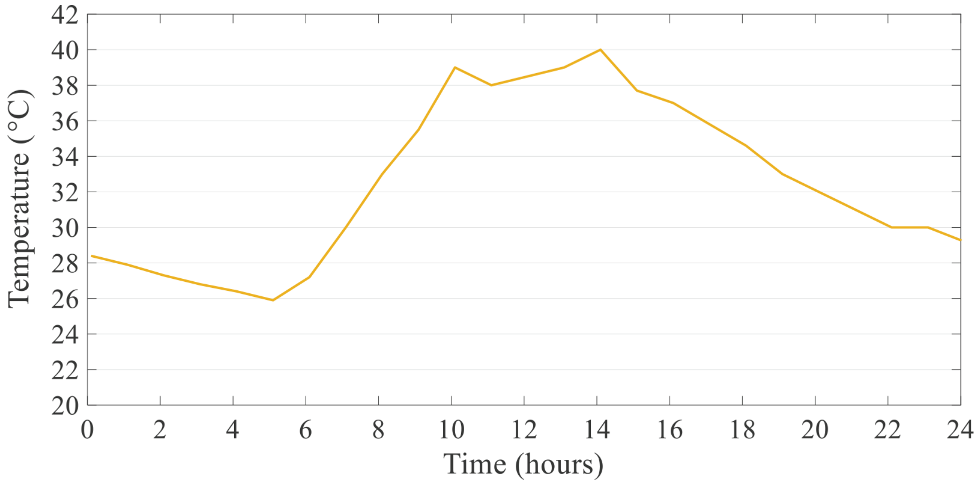

Figure 3: Outdoor temperature profile for July.

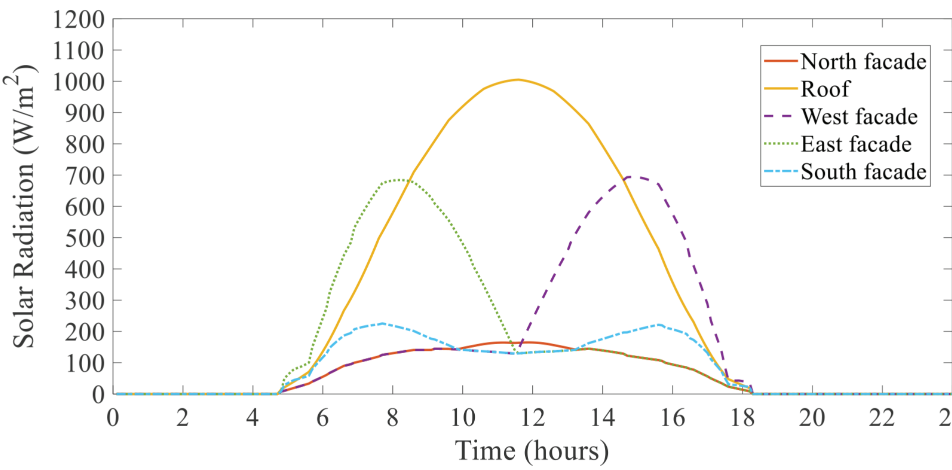

Figure 4: Solar radiation on different facades.

3.2 Description of the thermal zone and the thermal model

The thermal zone considered in this study is an office room with a floor area of 10 m^2. The walls, floor, and window *U*-values were selected to fulfil the requirements of the Dubai building code [10], which are presented in Table 1.

The floor is made of 10 cm concrete and represents the main thermal mass in the zone. Cooling load is limited to 2000 W maximum. The modelling approach used for this study is based on the lumped-parameter RC models, which have been shown to be practical for control studies [11]. This approach is generally valid when Biot number is less than 0.1, as in our case. In this approach, the thermal mass under consideration is discretized into a number of control volumes. Each of the discretized control volumes is represented by a node and is

Table 1: Dubai building code: envelope requirements.

Building element	Thermal transmittance
External walls	$U \leq 0.57$ W/m^{2}K
Roof	$U \leq 0.30$ W/m^{2}K
Windows (WWR > 40%)	$U \leq 1.70$ W/m^{2}K

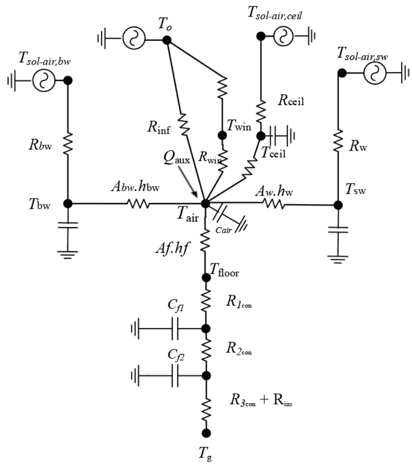

Figure 5: Thermal network model of the zone.

considered to be isothermal. Each of the nodes has a lumped thermal capacitance connected to it and thermal conductances connecting it to adjacent nodes. Considering the time interval (p) and time step (Δt), the general form of the explicit finite-difference model for the nodes with a lumped thermal capacitance can be stated as follows [12]:

$$T_{\mathrm{i,p+1}} = T_{\mathrm{i,p}} + \frac{\Delta t}{C_{\mathrm{i}}}\left(Q_{\mathrm{i}} + \sum_{\mathrm{j}} \frac{T_{\mathrm{j,p}} - T_{\mathrm{i,p}}}{R_{\mathrm{i,j}}} \right). \tag{5}$$

Where $T_{i,p}$ represents the temperature of node ‘i’ at time step ‘p’, $T_{j,p}$ represents the temperature of node ‘j’ at time step ‘p’, C_i is the thermal capacitance of node ‘i’, $R_{i,j}$ is the thermal resistance between nodes i and j, and Q_i is the heat source at node i.

Figure 5 shows the thermal network for the RC model of the zone. The main source of cooling is convective and is controlled based on the desired room air temperature. The sol-air temperature was assumed for the exterior surfaces to take into account the effect of solar radiation and is defined as follows:

$$T_{sol-air} = T_o + \frac{Q_{sol}}{h_o}, \tag{6}$$

where T_o is the outdoor (ambient) temperature, Q_{sol} is the incident solar radiation on each surface, and h_o is the outdoor heat transfer coefficient.

The following section shows the simulation results for a typical day in July, for which the outdoor temperature and solar radiation profiles were shown in Figs. 3 and 4, respectively.

4 RESULTS FOR FLEXIBILITY STRATEGIES

This section presents three strategies for pre-cooling the building before the peak demand period and utilizing building thermal mass to shift and reduce the peak load. Since flexibility is always relative to a reference case, our reference case here is considered as maintaining a constant indoor temperature of 24°C.

Figure 6 shows the simulation result for the reference case, including the cooling load and the air temperature for maintaining a constant indoor air temperature setpoint of 24°C, which is considered the reference temperature here, in agreement with DEWA recommendation (https://www.dewa.gov.ae/en/consumer/Sustainability/sustainability-and-conservation/cooling).

As observed, the cooling load profile follows the outdoor air temperature trend, which reaches its maximum around hour of 14. Due to the thermal mass of the building, the peak cooling load happens with some delays around 16.

4.1 Strategy 1: reducing the setpoint by 2°C

If we consider pre-cooling the building before the peak demand period and start decreasing the air temperature setpoint for some hours before, then certain changes in the load profile is observed with a certain potential for energy flexibility. As observed in Fig. 7, by lowering the setpoint by 2°C, from 24°C to 22°C, for 4 h (from 7 to 11), there will be changes in the cooling load profile, and consequently, there will be a reduction and shift in the peak demand. Also, about 1.7 h of zero load (11–12.7) is observed. The air temperature inside the building stays within the comfort range and does not pass the lower threshold of 20°C [13].

For this 4 h (7–11) ADR period, C_{ADR} is calculated from eqn (1) and is equal to $C_{ADR} = 317$ Wh/m^2. This value is representative of the thermal energy flexibility of the building. Then,

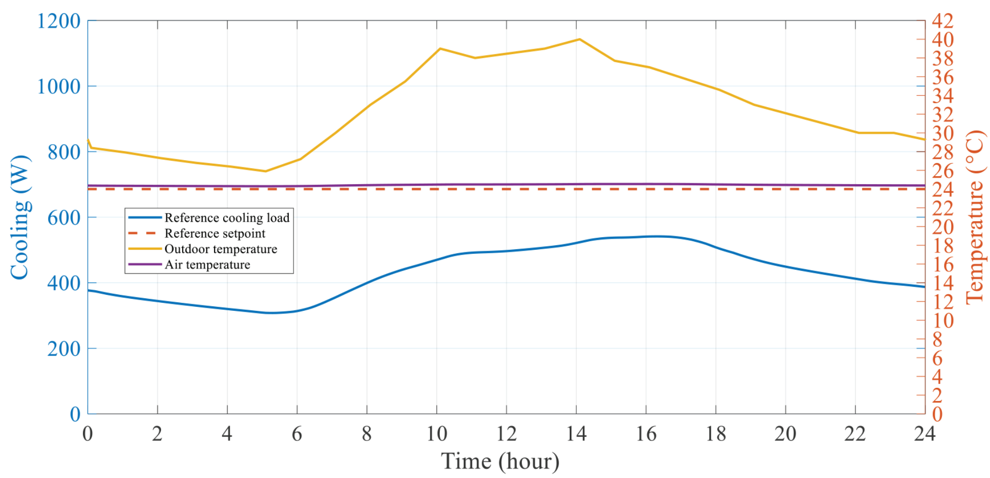

Figure 6: Cooling load based on the indoor reference temperature of 24°C.

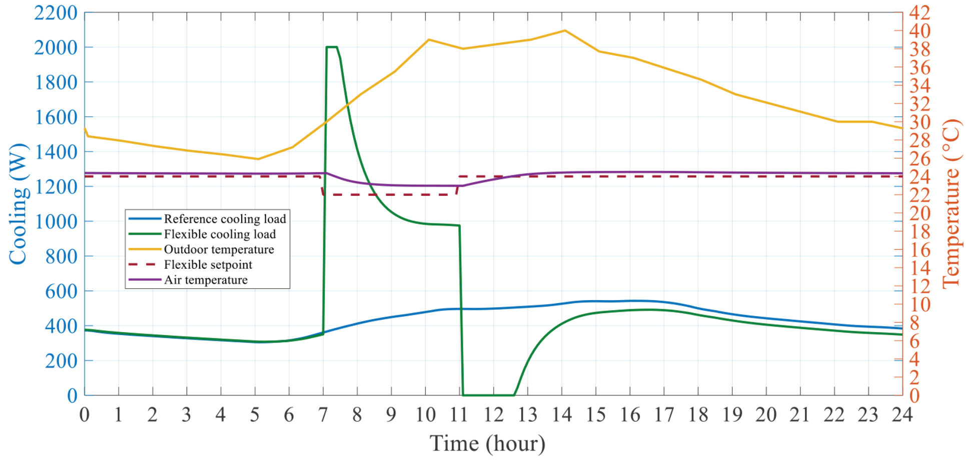

Figure 7: Flexible cooling load profile for 2°C setpoint decrease.

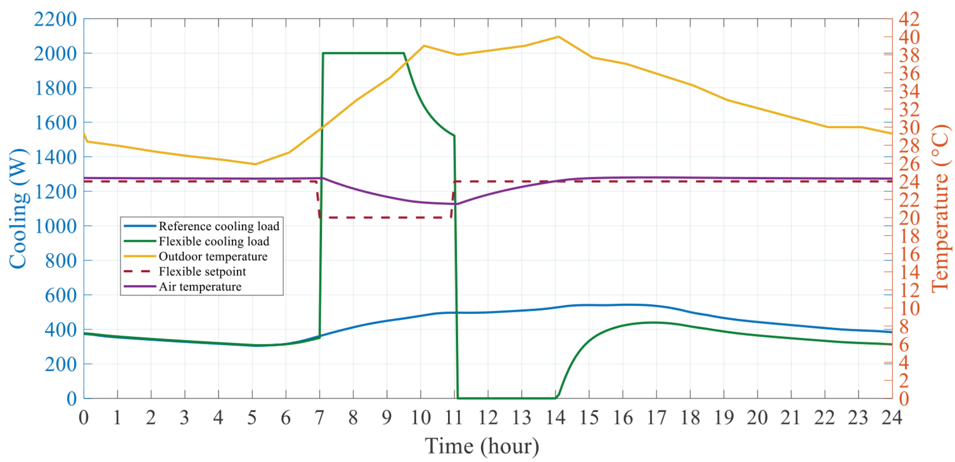

Figure 8: Flexible cooling load for 4°C setpoint decrease.

after that period, the storage efficiency is calculated as $\eta_{ADR} = 49\%$, meaning that 49% of the stored thermal energy during the ADR event is used subsequently to reduce the load and shift the peak for the remaining of the day.

4.2 Strategy 2: reducing the setpoint by 4°C

If the setpoint is decreased by 4°C (24°C–20°C) from 7 to 11, the cooling load will have the following profile shown in Fig. 8. As observed, this strategy will shift the peak load by more than 3 h from 14 to around 17 and provides about 3 h of zero load. The C_{ADR} for this case is 571 Wh/m^2, significantly higher than the previous strategy shown in Fig. 7. The efficiency for this case is calculated as $\eta_{ADR} = 46\%$.

4.3 Strategy 3: reducing the setpoint by 4°C using a linear ramp transition

If a smoother transition and smoother load change are desired, then a linear ramp trajectory can be considered for the setpoint transition from 24°C to 20°C. Figure 9 shows the result.

The cooling load and indoor air temperature follow a much smoother path. In this case, it is found that the C_{ADR} is equal to 389 Wh/m^2 and about 2.5 h of zero-load are obtained. Also, the storage efficiency is calculated as $\eta_{ADR} = 53\%$.

4.4 Strategies results recap

These strategies show that a typical building can provide considerable flexibility by simply modulating the setpoint before peak demand hours, thus aiding the power grid during critical periods. Also, in the case of an existing dynamic electricity tariff where the price of electricity can be higher during the peak demand hours, these strategies can save a considerable amount on the customer's electricity bill while being advantageous for the grid with the reduction in the peak demand. Table 2 summarizes the results for the three cases.

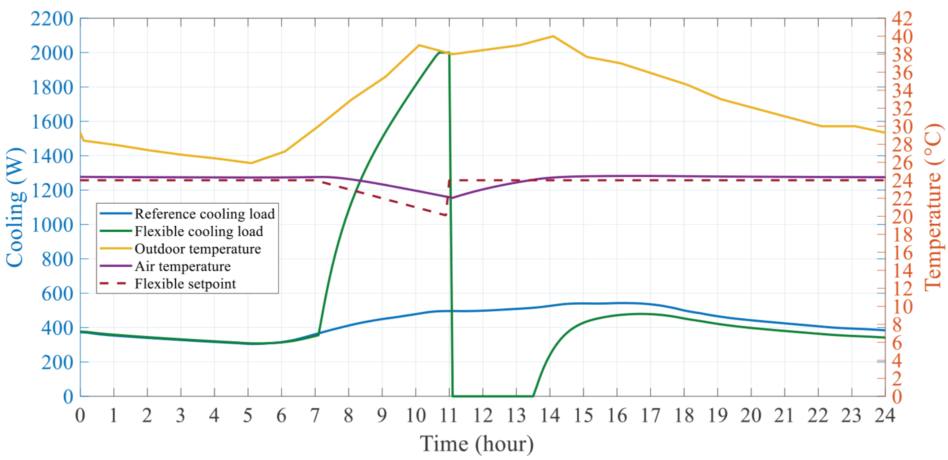

Figure 9: Linear ramp setpoint implementation.

Table 2: Summary of the strategies.

Strategy	Available structural energy storage capacity (C_{ADR})	Storage efficiency (η_{ADR})
Setpoint reduction of 2°C	317 (Wh/m^2)	49%
Setpoint reduction of 4°C	571 (Wh/m^2)	46%
Ramp setpoint reduction of 4°C	389 (Wh/m^2)	53%

5 CONCLUSION

This paper presented the assessment and quantification of the energy flexibility offered by a building with thermal properties in compliance with the Dubai building code and conditioned by an air source cooling system. The energy flexibility of the building under three strategies of temperature setpoint modulation on a typical day in July was evaluated. Two energy flexibility indicators, the available structural energy storage capacity (C_{ADR}) and the storage efficiency (η_{ADR}), were utilized for the analysis.

It was found that modulating the setpoint for certain hours offers the opportunity to use the building thermal mass for load management. Under the conditions of the study, about 317–571 Wh/m^2 of energy flexibility and the possibility of shifting the peak demand from 1.7 to 3 h were observed.

The quantification of the flexibility is valuable information for the grid that can be utilized when dealing with uncertainty in the production from renewable sources. For example, by knowing how much the aggregated flexibility can be expected from a group of buildings, the grid can ask the occupants to participate in an ADR event when needed, and this will be a significant contribution to keeping the stability of the grid. In future work, the strategies utilized in this study will be applied in a real building in Dubai to validate the quantified flexibility. As the energy flexibility is highly dependent on the type of the control strategy used for the HVAC system, it is also planned to study the effect of the control strategies in the Dubai climate.

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REFERENCES

[1] Bobmann, T. & Staffell, I., The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. *Energy*, **90**, pp. 1317–1333, 2015. https://doi.org/10.1016/j.energy.2015.06.082.
[2] IRENA, "Global energy transformation: A roadmap to 2050," 2019.
[3] IEAPVPS, "Snapshot of global PV markets 2021," 2021.
[4] GWEC, "Global wind statistics 2021," 2021.
[5] Government of Dubai. Dubai Electricity and Water Authority, Annual Statistics 2019, 2020. https://www.dewa.gov.ae/en/about-us/strategy-excellence/annual-statistics
[6] Reynders, G., Diriken, J. & Saelens, D. Quantifying the active demand response potential: impact of dynamic boundary conditions, 2016.
[7] Reynders, G., Amaral Lopes, R., Marszal-Pomianowska, A., Aelenei, D., Martins, J. & Saelens, D. Energy flexible buildings: an evaluation of definitions and quantification methodologies applied to thermal storage. *Energy and Buildings*, **166**, pp. 372–390, 2018. https://doi.org/10.1016/j.enbuild.2018.02.040
[8] Jensen, S. Ø., *et al.*, IEA EBC Annex 67 energy flexible buildings. *Energy and Buildings*, **155**, pp. 25–34, 2017. https://doi.org/10.1016/j.enbuild.2017.08.044
[9] U.S. Department of Energy (DOE). https://energyplus.net/
[10] Dubai Building Code 2021. https://www.dm.gov.ae/wp-content/uploads/2021/12/DubaiBuildingCode/

[11] Candanedo, J., Dehkordi, V. & Lopez, P. *A control-oriented simplified building modelling strategy*. 13th Conference of International Building Performance Simulation Association, Chambéry, France, 2013.

[12] Athienitis, A. K. & O'Brien, W., *Modelling, design and optimization of net-zero energy buildings*. Berlin, Wiley Ernst & Sohn, 2015.

[13] ASHRAE. Standard 55: Thermal Environmental Conditions for Human Occupancy, 2017.