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Aggregation of Energy Flexibility of Commercial Buildings

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Abstract: *Commercial buildings are increasingly utilised for providing demand side management due to their inherent thermal inertia and use of Heating, Ventilation and Air Conditioning systems. For a given demand response event, the question arises for the building manager or demand response controller on how to optimally provide flexibility, given different efficiencies and associated costs with each strategy. Current approaches often focus only on individual strategies as opposed to total available flexibility. This paper examines various demand response strategies simulated in a case study commercial building using an EnergyPlus model for the summer design day. Modified indicators are proposed for the available electrical energy flexibility and associated efficiency and daily profiles are created for the individual strategies. The total energy flexibility is calculated as a daily profile and the results show that the building was found to provide close to 1000 kWh energy flexibility at its peak.*

Keywords: *Building performance simulation; Energy flexibility; White-box models; EnergyPlus; Demand side management*

INTRODUCTION

The electricity grid of today has a greater share of renewable energy sources and it is predicted to keep increasing (EREC, 2011). This poses challenges to the grid in terms of stability with the fluctuating supply needing to be balanced with the demand (Lund *et al.*, 2015). Grid flexibility can be provided by either the supply side or demand side. Supply side flexibility is generally provided by using dedicated conventional power plants or storage to balance mis-matches in electricity production and demand (Lund *et al.*, 2015). Curtailment of renewable energy resources is also an option. Demand Side Management (DSM) is defined as a broad set of means to affect the patterns and magnitude of end-use electricity consumption (Lund *et al.*, 2015). DSM can be categorised as either reducing, increasing or rescheduling energy demand. Demand Response (DR), where consumers shift or curtail their electricity usage in response to financial or other incentives is one practical example of DSM.

Buildings represent about 40% of the total primary energy consumption in Europe (Economidou *et al.*, 2011) and this, combined with their potential for thermal energy storage, makes European buildings a very suitable candidate for DSM and for the provision of energy flexibility. The International Energy Agency (IEA) Energy in Buildings and Communities Program (EBC) Annex 67 is dedicated to building energy flexibility (Jensen *et al.*, 2017). The annex has focussed on the definition of energy flexibility in a building and the current working definition is given as *"The Energy Flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements. Energy Flexibility of buildings will thus allow for demand side management/load control and thereby demand response based on the requirements of the surrounding energy networks*" (Jensen *et al.*, 2017). The annex has also aimed to tackle the issue of a suitable indicator for energy flexibility.

Commercial buildings are of particular importance for the implementation of DR measures for several reasons. A single commercial building likely consumes as much electricity as hundreds of residential buildings and hence offers greater potential for shifting or curtailing electricity use. In addition, most commercial buildings usually require space conditioning (cooling and/or heating) and ventilation, and therefore use large Heating, Ventilation and Air Conditioning (HVAC) systems (Christantoni *et al.*, 2016). This HVAC load can be shifted using the thermal mass of the building. Most commercial buildings also have Building Automation Systems (BAS) or Building Energy Management System (BEMS) integrated with the HVAC systems. A BAS can be used to implement DR measures and ensure thermal comfort is maintained for occupants. Furthermore, a BAS can receive signals from the electricity grid directly (Hao *et al.*, 2012). Finally, commercial building operation schedules are more predictable than residential loads. For all of these reasons, commercial buildings are more favourable for implementing DR measures than residential or industrial buildings (Aduda *et al.*, 2017).

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DR programs need to be designed such that customers are motivated to participate. Generally, DR programs can be classified as either price or incentive based (Vardakas, Zorba and Verikoukis, 2015). Incentive-based programs pay customers to reduce their electricity usage at times requested by grid operators or aggregators. These programs are generally aimed at commercial and industrial customers and require a minimum power demand reduction. While not all individual customers are able to meet these minimum reductions, aggregators contract many smaller customers and offer their collective power demand reduction to the grid operator. Incentive-based DR is usually requested due to factors such as a spike in the demand or grid congestion. In theory, such DR events can occur at any time and on any day, although certain times of the day are predisposed because of typical peak consumptions. In most cases, DR event durations range from half an hour to two hours.

When a DR request is received by a customer, or alternatively, when a customer is deciding how much flexibility they can provide, assuming a large office building, the building operator faces the question of the optimal way to provide the flexibility with multiple competing objectives (Behl, Smarra and Mangharam, 2016). Even when provision of a power demand reduction is automated by a customer or end user, this decision still needs to be made. Commercial buildings, due to their size and complexity, are able to provide the flexibility through a range of options. Options may include using the building passive thermal mass, active thermal energy storage, onsite generation (solar photovoltaics (PV) or fuel generators) or electric storage (e.g., lithium-ion batteries or flywheels). Given numerous options, it is of interest to know the total available energy flexibility at a given time, not only to ensure maximal financial return but also to ensure minimal thermal comfort disruption to building occupants.

This present paper attempts to address this issue of calculating the total energy flexibility in a large commercial building. A case study building is considered with flexibility provided through several options as mentioned in the previous paragraph. Flexibility indicators from the literature are improved and presented, for both the individual DR strategies but also the aggregate (electrical) energy flexibility. The proposed methodology to assess the total available electrical energy flexibility and to ensure the optimal provision of flexibility for a given demand response event will be of value to both aggregator and building owners.

The paper is structured as follows. The 'Background' section focusses on the demand response strategies considered and the energy flexibility indicators used in literature. The identified research gap and aim of this study are presented to conclude this section. Next, the methodology used in the current study is presented, starting from the experiments performed on a white-box model. Finally, in the results section, the flexibility provided by the various technologies is quantified using the model and the total available electrical energy flexibility is calculated.

BACKGROUND

Demand Response Strategies

Lund et al. provides a comprehensive review of the different demand-side technologies available to provide energy system flexibility (Lund *et al.*, 2015). Existing research has focused on the use of the building thermal mass to shift consumption ((Aduda *et al.*, 2017), (Christantoni *et al.*, 2016), (Hurtado *et al.*, 2017), (Oldewurtel, Sturzenegger, *et al.*, 2013), (Reynders, 2015)) with various DR strategies taken into account. (Christantoni *et al.*, 2016) considered chiller water setpoint adjustments, fan control (on/off) and thermostat temperature adjustment. (Aduda *et al.*, 2017) considered cycling the air supply fan and cooling temperature set point reductions, and (Hurtado *et al.*, 2017) modified heat pump temperature setpoints.

Various other flexibility strategies have also been considered focusing on the comparison of the merits and demerits. The work of (Oldewurtel, Borsche, *et al.*, 2013) presented a unified framework that allows a comparison of different types of DR and energy storage resources. They compared batteries, plug-in electric vehicles (EV), commercial building thermal mass and thermostatically controlled loads (TCL). This study also considered a range of grid services offered by each resource. Peak load shifting control using different cold thermal energy storage technologies such as building thermal mass, thermal energy storage (TES) and phase change materials (PCM) were considered by (Sun *et al.*, 2013). The authors acknowledge the difficulties in even designing control strategies for load shifting using both thermal mass and TES, citing the computational burden. (Klein *et al.*, 2017) also compared several flexibility options including batteries, fuel switches, water tanks and building thermal mass. Two different supply methods were also considered, heat pumps and combined heat and power (CHP).

The work of (Pallonetto *et al.*, 2016) focussed on the development of a control algorithm for implementation of demand response strategies in a smart-grid compatible residential building. The control algorithm considered the heat pump, a TES, a PV array, solar thermal collectors for domestic hot water (DHW) and an EV. The drawback on

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this study was that the control strategy was implemented through the white-box EnergyPlus model, which puts limitations on the complexity of the control algorithms constraining it to rule-based control and the computational consequences of using a white-box model. However, Pallonetto et al. were still able to realise an overall annual economic saving of 16.5% for the residential energy cost.

Flexibility Indicators

There are a multitude of ways to quantify flexibility, which is evident when reviewing the literature in this area. A rigorous methodology is required when comparing flexibility between different DR technologies, and even more so when comparing different buildings. It is no surprise that there are numerous methods of quantifying energy flexibility when there are several different definitions of energy flexibility described in the literature. Through the work of Annex 67, a review was conducted of the different definitions of flexibility as well as some of the different proposed quantification methods (Lopes *et al.*, 2016). In addition, a review was provided of the different energy flexibility performance indicators together with the control strategies available (Clauß *et al.*, 2017). Suitable indicators are of use to building owners and aggregators in harnessing the flexibility their building or building portfolio can provide.

The indicators used in this study are based on the work of (De Coninck and Helsen, 2016) and (Reynders, Diriken and Saelens, 2017). The available storage capability (C_{ADR}) is defined as "the maximum amount of energy that can be added to the storage system during the duration of a specific flexibility event" (Reynders, Diriken and Saelens, 2017). De Coninck and Helsen have a similar definition and quantify this capacity by solving three optimal control problems. The available capacity for the upward and downward flexibility is proposed as follows:

$$C_{ADR} = \int_{j}^{l_{ADR}} \left| Q_j^{h,flex} - Q_j^{h,ref} \right| dt \qquad (1)$$

where, $Q_j^{h,flex}$ is the heating/cooling power for the upward or downward flexibility cases and $Q_j^{h,ref}$ is the reference control case. l_{ADR} is the duration of the demand response event.

The storage efficiency (η_{ADR}), which is defined as 'the amount of energy that is stored when activating flexibility that cannot be recovered after the flexibility event' is proposed by Reynders as follows:

$$\eta_{ADR} = 1 - \frac{\int_0^{hor} (Q^{h,flex} - Q^{h,ref}) dt}{\int_0^{l_{ADR}} (Q^{h,flex} - Q^{h,ref}) dt} \qquad (2)$$

Whilst this definition of storage efficiency works as intended for upward flexibility, i.e. when power consumption is increased, this definition cannot be used for downward flexibility provision. For downward flexibility, i.e. when power consumption is decreased for the demand response period through some action, a rebound effect is expected following this period. Hence, the storage efficiency needs to quantify the magnitude of the rebound effect.

Research Aim

Several papers have looked in detail at the potential flexibility that individual strategies can provide. However, for many commercial buildings, several of these options might be available, which can be used in parallel, either partially or fully. Hence, the identified research questions for the work described in this paper are as follows: "Can a suitable framework be identified that considers the various demand response strategies available in a commercial building? Can the various demand response strategies be aggregated to calculate the total flexibility that a building can offer?"

METHODOLOGY

This study uses a virtual DR testbed building rather than a real-world case study building. The reasons for this are that a virtual testbed building can be configured to include the various DR technologies that are to be studied. In future work, it is planned to apply the methodology described in this paper to a real-world case study building. First, a white-box model is developed and then it is used to analyse the potential for DR. The overall methodology is summarised below:

1. Build white-box virtual DR testbed model using EnergyPlus.
2. Using this virtual DR testbed model, analyse potential for demand response strategies initially for the summer design day case.
3. Quantify flexibility for these strategies individually and aggregate at hourly intervals using enhanced flexibility indicators.
4. Create a daily flexibility profile featuring the various demand response strategies (assuming independent DR events at every hour and that there is only one DR event in a day for use of the profile). Only down-flexibility results are presented in this study.

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White-box Model

For the virtual DR testbed building, a US-DOE (United States Department of Energy) commercial building archetype model was selected (Deru *et al.*, 2011). The DOE provides these reference models as EnergyPlus input files, which are intended to be used as starting points in energy efficiency research. Together, the archetypes represent approximately two-thirds of the commercial building stock in the USA (Deru *et al.*, 2011). The 'Large Office' reference building model (shown in Figure 1) was selected for this study, as many of the flexibility strategies that are considered within this paper would be applicable to large office buildings. The version with "new construction", which comply with the minimum requirements of ASHRAE Standard 90.1-2004, was selected for climate zone 4C. The weather data used is that of Dublin, Ireland, the location of the virtual test bed. The large office has a floor area of 46,320 m^2 over 12 floors (plus a basement). The building operates from 6.00 am to midnight on weekdays and 6.00 am to 5.00 pm on Saturdays (with no occupancy on Sundays). The building has a 'Mass Wall' (Continuous insulation) wall type based on ASHRAE Standard 90.1-2004 with a U-Value of 0.857 $W/m^2.K$ (Deru *et al.*, 2011). A simulation time-step of 15 minutes was selected as this an appropriate compromise between modelling the fast-dynamics and the data-burden from simulating short time steps over large prediction horizons (Sturzenegger *et al.*, 2016).

The large office reference building has a gas boiler for heating (1,766 kW), two water-cooled chillers (each 1,343 kW) for cooling and a multizone variable air volume (MZ VAV) for air distribution.

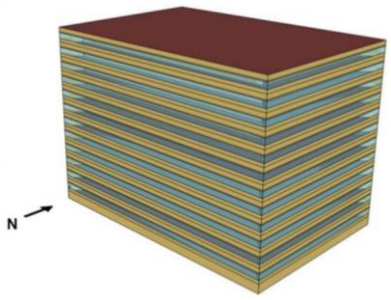

Figure 1: 'Large Office' Building Archetype Model

The building was also modified to add a lithium-ion battery to provide a means of energy storage and source of energy flexibility. A 1.5 MWh two-hour duration battery of 500 kW discharge was selected and implemented in the EnergyPlus model using the "ElectricLoadCentre: Storage:Simple" object class.

To include onsite generation, a solar PV array was also added to the building roof. The PV array has a rated power output of 200 kWp. The PV array tilt was set at 53° from the horizontal to optimise its energy production throughout the year. The fraction of the roof with active solar cells was assumed to be 46%, based on technical assumptions identified in (Gagnon *et al.*, 2016). The PV solar cell efficiency was set to be 20% (Gagnon *et al.*, 2016).

Demand Response Strategies

This study focusses initially on the available electrical energy flexibility for the summer design day. The load profile for this day was generated using the EnergyPlus model to obtain an indication of the electrical power demand and associated building end-use breakdown for the case study DR testbed building. This analysis considers the suitability of different loads for participating in DR at different times of the day. The load profile on the summer design day (with a max ambient temperature of 24°C) is shown in Figure 2. The chiller load peaks around 4.00 pm to 6.00 pm due to the effect of solar gains. The fan and pump loads are small relative to the total consumption. The summer peak consumption is around 6.00 pm when the cooling load is the highest.

First, considering the building passive thermal mass as one of the technologies that can provide flexibility, adjustment of the global temperature setpoints can be used as a DR strategy, i.e., basically shifting the cooling load. This is the most common DR strategy used as there is a strong correlation between air temperature setpoints and building energy consumption. For the sake of this study, zone pre-conditioning is not considered to allow easy comparison between the various strategies and assuming no warning before a DR request. Operative temperature drift values are given in (*ASHRAE 2004b Standard 55. Thermal Environmental Conditions for Human Occupancy*, 2004) (see Table 1). These drift values are used in this study for this DR strategy.

Another DR strategy is to adjust the chiller water setpoint temperature. An increase of the chilled water temperature will reduce the chiller electrical power demand. In this study, the chiller water temperature setpoint is increased from the normal 6.7°C to 12°C (this is less than the upper operational temperature limit for the chiller in question). Following this measure, there are usually undesirable rebound effect demand spikes. Rebound avoidance techniques such as recovery periods were not considered in this study as this is conservative in terms of the flexibility

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able to be provided. For this strategy, the air flow rates were locked to the reference values to prevent compensation by the air handling units (AHU).

Table 1: ASHRAE acceptable limits for zone temperature drift (ASHRAE 2004b Standard 55. Thermal Environmental Conditions for Human Occupancy, 2004)

Time Period	0.25 h	0.5 h	1 h
Maximum Operative Temperature Change (°C)	1.1	1.7	2.2

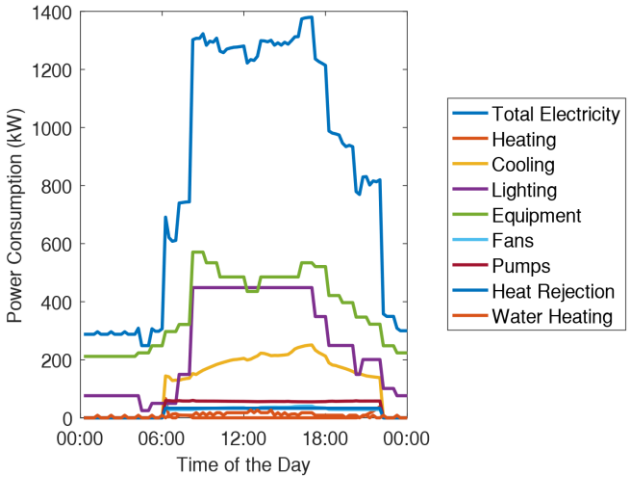

Figure 2: Load Profile – Summer Day (July 10th)

Another common DR strategy is to modulate the fan mass flow rate (or fan speed) during the DR period, although apart from thermal comfort, minimum ventilation/ACH requirements need to be considered. The AHU supply fans are VAV units which vary the air flow to meet the demand. Only down flexibility (i.e. a reduction in the fan mass flow rate) is considered. The air mass flow rate is set to 20% of the reference (variable) flow rate (20% modulation) and the cooling loop pump mass flow rates are also modulated to prevent compensation.

The battery provides a means of shifting energy consumption and the use of this storage is another DR strategy considered in this study. The sizing of the battery will have an effect on this energy flexibility, but this is not considered in this study. The use of the battery as a flexibility source comes at a cost due to efficiency losses in charging, discharging, in the inverter and parasitic losses.

In this study, the PV, whilst not considered a DR strategy, does reduce imported power and is considered for comparison purposes. Future work will consider the PV and battery as a coupled system providing energy flexibility with the battery only charging from the PV output.

With respect to the DR strategies mentioned above (summarised in Table 2), a flexibility window of 1 hour in duration is considered, allowing a daily profile to be created of the flexibility available. The daily fluctuations in the available storage capacity due to the impact of occupancy schedules have already been studied (Reynders, 2015). In this work, the concept is extended to study how the flexibility available and its associated efficiency vary daily.

The DR strategies listed in Table 2 are implemented for the cooling design day, according to the TMY data for Dublin.

The DR strategies were implemented in EnergyPlus using the Energy Management System (EMS). The control actions are implemented using the EnergyPlus runtime language (Erl) within the EMS programs.

The performance of each strategy was initially determined by comparing against the case where no DR strategy is implemented. The difference in the building electrical power demand and influence on occupant comfort are the main variables compared. Influence on occupant comfort was considered by looking at the predicted mean vote (PMV) index of the Fanger thermal comfort model (Hurtado *et al.*, 2017) and the carbon dioxide (CO_2) levels in parts per million (ppm) where applicable.

Table 2: Summary of Demand Response Strategies (Down-Flex)

Demand Response Strategy	Details
Chilled Water Temperature Adjustment (CWT)	CWT increased from 6.7°C to 12°C
Global Setpoint Adjustment (GSA)	Setpoint Adjustment per ASHRAE 2004b limits
Fan Modulation	20% of reference variable mass flow rate
Battery	
Solar PV(1)	

(1) *included only for comparison purposes and because it reduces purchased power*

Flexibility Quantification

The flexibility indicators used in this study are specified with reference to the indicators used originally by (Reynders, 2015) and then further in (Reynders, Diriken and Saelens, 2017). The available storage capacity (C_{ADR}) as it is used in this study is similar to the definition introduced by (Reynders, 2015). The key difference is that

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P^{flex} and P^{ref} refer to the building electrical power consumption and not the thermal heating/cooling powers. This makes the indicator directly applicable from a grid perspective. It is also renamed the "Available Electrical Energy Flexibility" (AEEF) to encompass DR strategies that are not based on either active or passive storage of energy.

$$Available\ Electrical\ Energy\ Flexibility\ (AEEF) = \int_j^{l_{DR}} |P_j^{flex} - P_j^{ref}| dt \quad (3)$$

where l_{DR} is the duration of the demand response event. The storage efficiency (η_{ADR}) is defined separately based on whether up-flexibility or down-flexibility is provided. For the case of down-flexibility, when power is modulated down during the period of demand response, a rebound effect is expected following the period of demand response. Hence, the efficiency is a measure of the magnitude of the rebound effect over the amount of energy shifted (or available electrical energy flexibility). This is defined as:

$$\eta_{AEEF}(down - flex) = 1 - \frac{\int_0^{hor} (P^{flex} - P^{ref})^+ dt}{\left| \int_0^{hor} (P^{flex} - P^{ref})^- dt \right|} \quad (4)$$

The positive sign superscript refers to only the positive area (when $P^{flex} - P^{ref} > 0$) in the $P^{flex} - P^{ref}$ curve and the negative superscript refers to the negative area in this curve. For up-flexibility, the definition is:

$$\eta_{AEEF}(up - flex) = \frac{\left| \int_0^{hor} (P^{flex} - P^{ref})^- dt \right|}{\int_0^{hor} (P^{flex} - P^{ref})^+ dt} \quad (5)$$

For the energy flexibility provided by batteries, equation (5) is applicable to both down and up flexibility. Considering the case of down-flexibility provision, using this equation, given that the amount of energy discharged is exactly equal to the amount of energy used to recharge the battery to its original SOC, the numerator in equation (5) would equal zero resulting in an efficiency of 100%. Table 3 summarises the equations used to calculate the efficiency for each of the DR strategies.

Table 3: Efficiency Calculation of DR Strategies

DR Strategy	CWT	GSA	Fan Modulation	Battery
Up Flex	Eq. (5)	Eq. (5)	Eq. (5)	Eq. (5)
Down Flex	Eq. (4)	Eq. (4)	Eq. (4)	Eq. (5)

RESULTS & DISCUSSION

Individual Energy Flexibility

The analysis of one particular DR event is illustrated first. In this case, the CWT demand response strategy is utilised with a CWT setpoint modulation from 6.7°C to 12°C for the demand response duration of 1 hour between 1.00 pm and 2.00 pm to provide downwards flexibility. Figure 3 shows the difference in power consumption due to the demand response strategy, the two important features being the decrease in power consumption during the demand response duration and the rebound effect following this.

From this, using equation (3), the flexibility (AEEF) can be calculated for the DR period (141 kWh). This is essentially the area under the graph of the difference in power consumption of Figure 3. Using equation (4), the associated efficiency of activating the energy flexibility can be calculated (91.8%). Repeating this process for every hour of the day (assuming independent DR events at each hour), a daily profile can be obtained for the Available Electrical Energy Flexibility (Figure 4) and associated efficiency (Figure 5). Figure 4 shows that the CWT strategy can only provide energy flexibility during the chiller operation hours (6.00 am to 10.00 pm). The available electrical energy flexibility peaks around 5 pm when the cooling load is the highest and hence the chiller output is the highest. The efficiency of the CWT strategy is constant around 90-100% throughout the operating hours of the chiller. It is noted that an efficiency of 100% for the down flexibility provision corresponds to no rebound following the DR event.

For the following DR event and all those considered in this study, it was ensured that the PMV fanger thermal comfort value did not exceed the -1 to 1 comfort band during the DR event period.

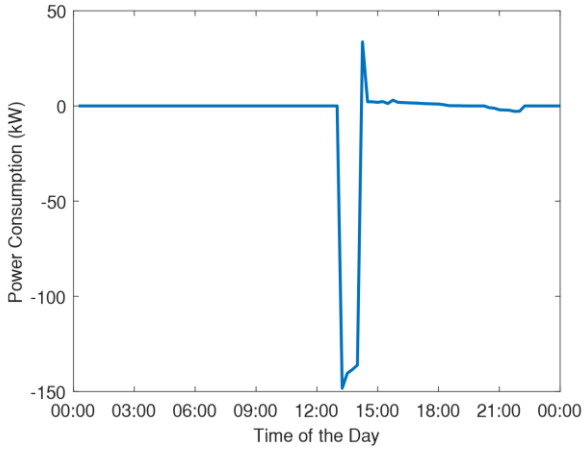

Figure 3: Difference in Power Consumption for CWT Adjustment DR Strategy (1.00 pm)

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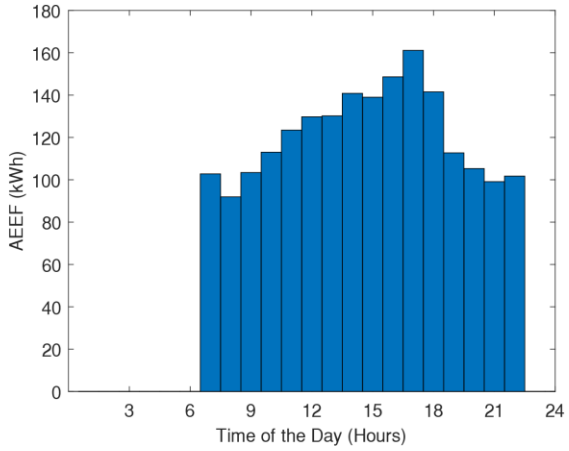

Figure 4: AEEF – CWT Adjustment DR Strategy – Daily Profile

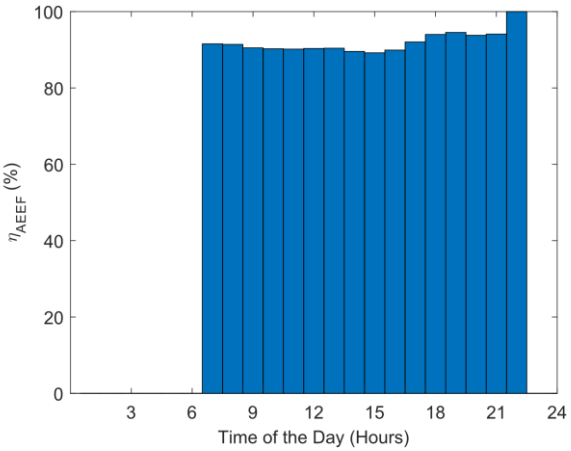

Figure 5: η_{AEEF} – CWT Adjustment DR Strategy – Daily Profile

The daily profiles (for the summer design day) of available electrical energy flexibility for all the DR strategies (down flexibility) listed in Table 2 are illustrated in Figure 6 as a carpet plot. The battery provides an almost consistent amount of energy flexibility around 460 kWh (note that even though the battery is rated for a discharge of 500 kW, the inverter efficiency lowers the actual flexibility). During the unoccupied hours, the available flexibility is limited by the lower total building power demand. The PV output, which also reduces the purchased electricity, peaks as expected around midday. The global setpoint adjustment DR strategy results in the smallest difference in power consumption. All DR strategies that modulate the HVAC system are only able to provide energy flexibility during the occupied hours when the chiller and fan are operating. The fan modulation DR strategy provides the next largest amount of flexibility. For this DR strategy, it was ensured that CO_2 levels stayed under the limit of 1000 ppm as per ASHRAE 62 standard (*ASHRAE STANDARD Ventilation for Acceptable Indoor Air Quality*, 2004).

Figure 7 shows the efficiency of all the DR strategies for the summer day as a daily profile. Using this information, a priority list can be constructed for every hour of the day ranking the different strategies in terms of efficiencies. Note that the efficiency is shown as 0 when the AEEF is equal to 0. The battery efficiency is constant around 50-60% and this is a combination of the charging, discharging and inverter losses. The efficiency of the fan modulation DR strategy dips during the middle of the day when occupancy is the highest. This is expected as a larger rebound would be expected with the higher internal gains and greater solar gains during this period. The efficiency of this strategy peaks near the evening when the rebound effect is limited by the cooling system turning off for the night. The efficiency is 100% for some of the DR strategies in Figure 7 at certain times of the day and the reason for this is explained below using an example.

Taking the example of a one-hour demand response strategy of adjusting the global setpoint temperature at 5pm, in this case (Figure 7), there is a rebound effect following the DR event as fan and pump loads increase to meet the normal setpoint again (similar to that observed in Figure 3). However, the overall reduction in cooling load following the DR duration is greater than the rebound. Hence, further load reductions occur following the DR event. Using equation (4), this leads to an efficiency of 100%. This only occurs in this case as the control strategy used by the HVAC system is simple rule-based control and hence energy consumption is not as optimised as optimal or model predictive control cases.

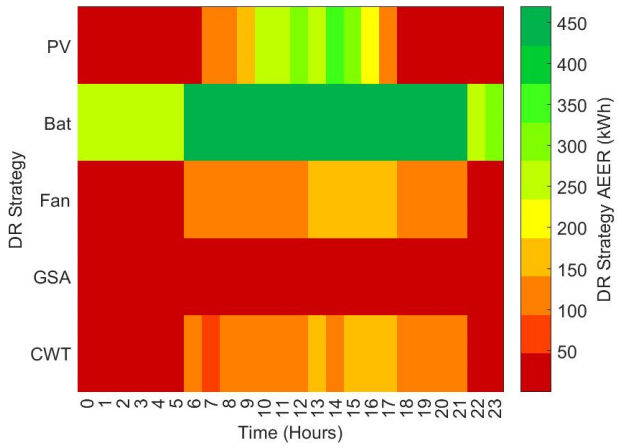

Figure 6: AEEF – All DR Strategies (Down Flex) – Daily Profile

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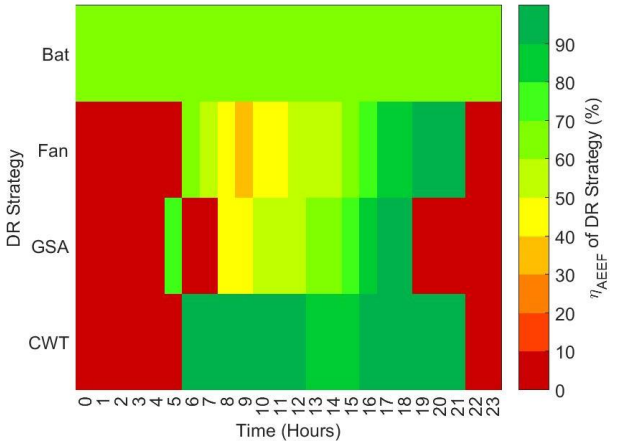


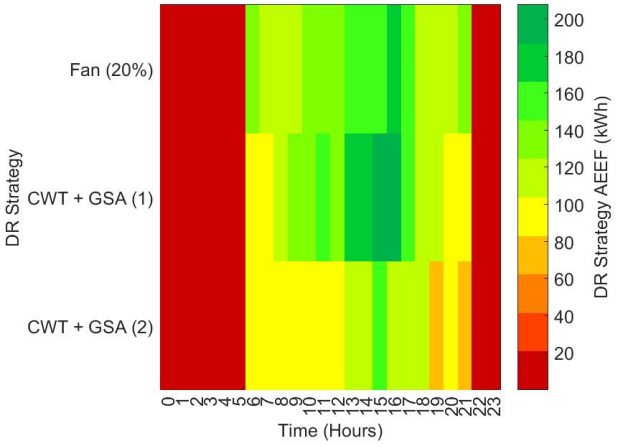
Figure 7: η_{AEEF} – All DR Strategies (Down Flex) – Daily Profile

A building operator can use the information given in Figure 6 and Figure 7 together to act in the context of a given demand response event. In the case where the energy flexibility requested is greater than that provided by any individual DR strategy, a combination will have to be used. In this case, care needs to be taken as the aggregated energy flexibility provided by a combination of DR strategies may not simply be the aggregated individual energy flexibility values. This is investigated further in the next section.

Aggregated Energy Flexibility

The chiller water temperature adjustment and global setpoint adjustment strategies are capable of being combined and their combined available electrical energy flexibility (through simulation) is compared in Figure 8 (CWT + GSA (2)) with the summation of the individual flexibility values from each of the respective strategies (CWT + GSA (1) in Figure 8). A comparison is also made with the flexibility that is available from the fan modulation DR strategy. These results show that the energy flexibility from both strategies cannot be simply summed together and need to be simulated together. The fan modulation DR strategy provides greater energy flexibility than both these strategies combined and hence is considered in combination with the battery strategy and PV.

The total available electrical energy flexibility from the building is illustrated in Figure 9. This figure shows that the building is capable of delivering almost 1000 kWh (for a duration of one hour) of energy flexibility to the grid around 3.00 pm. This amount is less than the maximum hourly energy consumption of around 1400 kWh (Figure 1). This reduction is also possible without the thermal comfort of the building occupants being impacted detrimentally.



Note: CWT + GSA (1) – individual sum (mutually exclusive)
CWT + GSA (2) – combined simulation (mutually inclusive)

Figure 8: Aggregation of CWT & GSA DR Strategies & Comparison with Fan Modulation DR Strategy

One of the limitations of this approach to presenting energy flexibility is that only one-hour DR durations are able to be captured. Further information is required to estimate the energy flexibility for longer DR durations. Further, this profile is only applicable in the case of one DR event during a 24 hour period. The provision of energy flexibility would affect the available energy flexibility in the following hours.

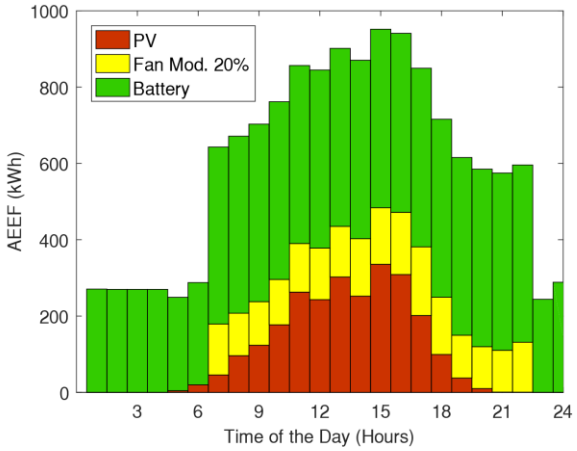


Figure 9: Aggregation of PV, Battery & Fan Modulation DR Strategies

CONCLUSIONS

A methodology has been shown here for quantifying the available electrical energy flexibility from various DR

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strategies commonly available in a large commercial building and presenting the total energy flexibility. The results show that the energy flexibility of various DR strategies cannot simply be summed as strategies may interact due to coupling of the systems. In these cases, simulation is required with the strategies applied in conjunction to calculate the total energy flexibility.

Modified indicators for the energy flexibility (*AEEF*) and associated efficiency (η_{AEEF}) of the provision of the energy flexibility have been derived based on existing indicators proposed in current literature (C_{ADR} and η_{ADR}). These new indicators are more generalised to the various DR strategies available in a building and are able to consider the efficiency for both up and down flexibility provision. They are also more applicable for use from the grid-side dealing directly with the building power consumption rather than heating/cooling thermal loads. This information is presented in the form of daily profiles, which are useful to building operators in the provision of maximal energy flexibility for a demand response event but also with minimal thermal comfort disruption.

The 'large office' archetype model is capable of providing close to 1000 kWh of available electrical energy flexibility around the early afternoon period through a combination of modulating the fan airflow rate, shifting load through the battery installation and the generation from the PV.

This paper only presented results for the down-flexibility case; future work will present the results for the up-flexibility case. While this study was focusing only on a cooling day case, this methodology also works for a heating day case, and in fact can be repeated for any day. Further work could investigate how this information could be presented on a yearly level without losing the granularity of the daily profile information. Future research work will also add a TES to the building and consider any new DR strategies arising from this.

This methodology as proved using this case study can capture the flexibility available from the various DR strategies available in a large commercial building and considers the various efficiencies as well as the aggregation of the various strategies in response to a DR event. This work allows us to unlock the full energy flexibility potential of a large commercial building.

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NOMENCLATURE

A_{EEF}	Available Electrical Energy Flexibility
C_{ADR}	Available Storage Capacity
hor	Simulation horizon (24 hours in this study)
$l_{ADR/DR}$	Demand response duration
η_{ADR}	Efficiency of storage
η_{AEEF}	Efficiency of AEEF
P_j^{flex}	Electrical power consumption of DR case
P_j^{ref}	Electrical power consumption of reference case
$Q_j^{h,flex}$	Thermal heating energy of DR case
$Q_j^{h,ref}$	Thermal heating energy of reference case

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