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The potential and possible effects of power grid support activities on buildings: an analysis of experimental results for ventilation system

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Abstract—**This paper reports on the potential and possible effects of using building services installations (notably ventilation systems) to support power grids. This is significant taken that the shift towards smart grids comes with adoption of demand side integration and the concept of active controllable loads. However, it is recommended that demand side resource will be used for grid support activities only if non-disruption in terms of indoor comfort and their responsiveness can be guaranteed. Relevant studies mainly report grid perspective in event of using demand side resources to support the power grid. The result is that little emphasis is given to indoor comfort, building behavior and the exact details of achieving controllability at building level in such events. Using experimental data from an office building in the Netherlands this paper reports on indoor comfort and building behavior in the event of committing installed ventilation systems to provide power grid support services. Possibilities for attaining controllability and responsiveness for the components in such systems are also presented. The study is case specific and contributes to the development of possible operational guidelines for building ventilation systems in event of using them for grid support activities.**

Keywords—Buildings, Ventilation Systems, Cooling Systems, Demand Side Resources, Grid support

I. INTRODUCTION

The purpose of this paper is to outline potential and possible effects of using buildings for grid support activities within the framework of smart electrical grids[1]. In smart electrical grids buildings are not only supplied with electricity but are also able to offer services to power grids. In office buildings, comfort has been shown to have direct effect on productivity and wellbeing of occupants. At the same time, comfort provision impacts on energy consumption. For example, use of ventilation and cooling systems together with other thermal and indoor air quality systems account for up to 70% of building energy use [2]; of this, 48% on average are derived from electricity in the European Union region [3]. In summer which is the focus period of the study up to 90% of the building energy is attributed to electricity for most countries in Central Europe [2], [3]. There are five common categories of services that buildings may offer to the grid [4]: energy efficiency, price response, peak shaving, reliability response or regulation response. Reliability and regulation response services from building based loads is a fairly recent conceptualisation and is still under experimentation; in addition, they are associated with obstacles in form of legislative barriers and enormous number of generation sources required to deliver meaningful service [5]. When offering service to the grid, it is important that comfort remain central for buildings. The idea of grid support activities by buildings in the context of electrical smart grid has led to a change of electrical energy supply chain organization at low voltage levels. Consequently, new concepts like 'active load' and 'demand side integrations' are now a norm [6], [7]. Active loads are unique in their ability to reliably deliver service to the power system whilst also maintaining quality primary service to building occupants [6]. In modern context the concept of active loads require multi-level control spanning across different timescales such as milliseconds, seconds, minutes and hours. It is also noted that different timescales are associated with respective systems involved from bulk generation stations all the way to the feeder line and the power meter box. At the same time it requires delivery of both traditional supply side and demand side power services in a manner that is efficient and cost effective. On a wider scale this is referred to as demand side integrations (DSI). DSI refers to a market oriented management philosophy that acknowledges joint responsibility of conventional electrical power supply side and demand side (buildings) in providing support to the power grid [8]. This is a departure from the past whereby demand side management (DSM) was the norm and the approach concentrated on peak reduction, peak shifting, strategic load growth, valley filling and energy conservation at the building side; this was rather static in nature and not very far reaching. DSI integrates the idea of dynamic response and management with the traditional DSM roles such that dynamic energy management for both demand and supply sides is emphasized as much as energy efficiency. The advantage of DSI is that it ensures that energy resources and infrastructure are used in a more flexible and economical manner as cooperative approach is emphasized. A number of studies exist on using demand resources to provide power grid support services; these studies highlight the following issues amongst others:

- Heating, Ventilation and Air Conditioning system loads are favored for use in DSI schemes due to the fact that they are composed of variable frequency drives which can be marshalled to action quickly by reducing their speeds without compromising comfort, thermal mass of most buildings enables them to have longer transient times for reduction of thermal comfort after withdrawal of HVAC services [9], [10].

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[1] Smart electrical grids are defined as upgradable electricity network with enabled multi-directional communication between sources, loads and components often occurring at low voltage regions [1]

- DSI require immediate response, this makes latency and reliability of the communication system highly crucial. Ventilation loads in buildings were shown to achieve response time of less than 20 seconds when used within open information sharing networks [11].
- Automation of response by buildings for grid support activities is only practical and cost effectiveness with aggregation of large numbers of participating loads [10], [11].
- Occupants acceptability, cooperation and collaboration is critical [9]–[12]. This is important because service provision by buildings to the grid may sometimes occur at the borderline of allowable comfort. Indoor comfort guidelines are discussed in Section II.

However, these studies over-simplify the full potential, implications or effects on buildings should they be used for grid support activities. Further studies are as a result needed on the building side to properly definition limits of operational flexibilities, systems response times, comfort recovery time and possible productivity effects when using buildings to provide grid support activities. In line with this, the paper attempts to unravel the potential and possible effects of using ventilation systems installed in buildings for grid support services. This paper is within the framework of a project that aims at developing a new generation building energy management system with enabled intelligence for operations with the smart grid. The argument pursued in the paper is that buildings as auxiliary infrastructure to smart power grids require to be equally intelligent[2] for optimal gains in the interactions [14], [15]. The reference gains in this context must be within confines of acceptable indoor comfort boundaries.

II. Indoor Comfort Boundaries

Indoor comfort is an aggregation of characteristics defining indoor thermal, air quality, visual, aesthetics, and aural aspects. Key indoor comfort parameters that greatly influence energy consumption are those related to thermal, air quality and visual characteristics [2], [3]; these energy influencing comfort parameters are critical in the interactions with power grids. Specifically, parameters considered relevant in this study are those related to air quality (ventilation rate, carbon dioxide concentration, relative humidity) and thermal comfort (because the system is reliant on ventilation for cold air distribution). Traditionally comfort in buildings is measured in terms of PMV and PPD[3]. Values (with $-0.5 < PMV > 0.5$ and $PPD < 5\%$ considered as most comfortable and $-1 < PMV > 1$ and $PPD < 10\%$ as acceptable). As an alternative, adaptive thermal comfort approach has been suggested for specifying thermal comfort, in this method indoor occupants ability to adapt to the indoor environment is taken into consideration and only requires the characterisation of indoor temperature as a function of ambient outdoor temperatures [17], [18]. In relations to our experiment (taking into account the summer duration and the case study), the following comfort boundaries were applicable:

- for a maximum of 100 hours annually, an indoor air temperature of $25°C$ and for a maximum of 20 hours annually, an indoor air temperature of $28°C$ [19]. However, it is noted that the aim is to ensure that service is delivered to the grid with minimal thermal discomfort (that is with indoor temperatures below $25°C$).
- carbon dioxide concentration $< 800ppm$.
- air velocities $> 0.25m/s$.
- relative humidity $< 70\%$ be maintained at all times.

The Building Management Systems (BMS) are crucial in ensuring that indoor comfort criteria is maintained. BMS are electro-mechanical control systems largely tasked with improving the interaction among integrated sub-systems and building users to achieve maximum comfort and reduced energy costs [20]; in modern times this also includes undertaking detailed energy analysis and complete energy management of buildings [21]. The BMS therefore plays a key role during grid support activities by building; the details of this is however not the focus of the study. Further parts of this paper are methodology, results and discussion, conclusion, acknowledgements and references.

III. Methodology

The paper aimed at illustrating potential and possible effects of using ventilation systems installed in buildings to provide power grid support services. To realise this aim, a three stage process was embarked on, these were: 1) quantifying possible energy advantages that can be derived from flexible operations of the cooling and ventilation systems such as peak load reduction/shaving, peak load shifting, energy efficiency potential and dynamic energy management opportunities; 2) evaluation of associated comfort parameters during the period of flexible operation of cooling and ventilation systems; and 3) rationalisation of possibilities for realising controllability and responsiveness for the cooling systems.

A. The test bed

An office building in the Breda, Netherlands was used as a study. The test building has three floors with an approximate total floor area of 1540 m^2. The average occupancy of the building is 35 people. The electrical supply system at the test building can be modelled as shown in Figure 1. Key component system groups allowed for in the electrical system are cooling, humidifier, ventilation, lighting and office appliances. The ventilation system which is the main focus of this paper is made up of a fan rated at 9.5kW dedicated to serving the 3 main cooling zones. The toilet facilities in the building is served by independent/dedicated exhaust fans; these are not included in discussions herein. Total ventilation fan capacity is $15000m^3/h$; ventilation capacity as distributed for north, south and electrical zones are $8125m^3/h$, 4598 m^3/h and 2420 m^3/h respectively.

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[2] Intelligence for buildings describes ability to achieve functional requirements whilst also adhering within the bounds of pre-established associative environmental quality norms or standards [13]

[3] Fanger [16] describes: (1) PMV as calculable variable based on heat balance on an assumed average human being based on their thermal perception on the basis of hot, warm, slightly warm, neutral, slightly cool, cool and cold, and (2) PPD as the percentage of the number of indoor population that are dissatisfied with the indoor climate.

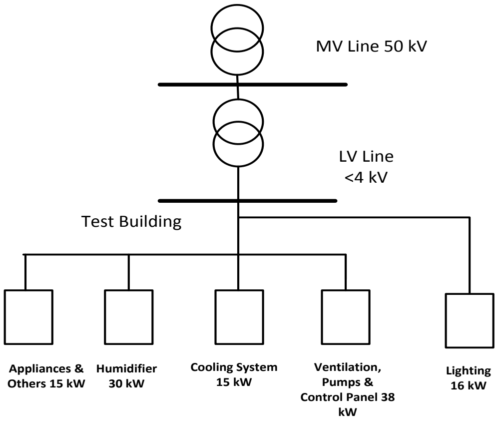

Fig. 1. Electrical system at the test building, by installation capacity.

B. The concept

In the experiment energy consumption and comfort profile were captured at 100% nominal operational capacity for the ventilation system. For energy consumption, measurement was done using electric meters that digitally enabled to log data into a proprietary web based Building Management Systems. The actual power consumption measurements in kW recorded for every second. For comfort profile, ambient air temperature, room temperature, relative humidity and carbon dioxide concentration were recorded using wireless sensor networks operating with a version of Zig Bee protocol (plugwise devices). These were then logged on into an independent squirrel logger then transmitted to a central server every second. The ventilation system was then adjusted to operate at 75% nominal setting and measurements taken for comfort and energy consumption parameters. This was done for 30 minutes. The short intervals for operational adjustments ensured that comfort boundary conditions were not breached during experiment. The reduction of nominal operational capacity for the ventilation fan also has a cascading reduction in the operational capacity of the cooling machine as less air is available for cooling.

Due to the fact that comfort data for 75% nominal ventilation system setting were minimal, the study implemented a prediction method, namely Artificial Neural Network (ANN) using the Neural Network toolbox in Matlab with the default settings. To learn the parameters of the ANN we used the non-linear autoregressive model with two time series as input 'NARX' (that is, the last hours of the T, RH and CO_2 plus their corresponding ($\{$minute$\}$ states), and the Levenberg-Marquardt optimization algorithm [22]). In order to characterize the accuracy of our model we use two metrics: i) The root mean square error (RMSE) is define by $RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(v_i - \hat{v}_i)^2}$, where N represents the total number of data points and, ii) the correlation coefficient (R) indicating the degree of linear dependence between the real value and the predicted value is define, by:

$$R(x, x') = \frac{E[(x-\mu_x)(x'-\mu_{x'})]}{\sigma_x \sigma'_x}$$

where E is the expected value operator with standard deviations σ_x and σ'_x; μ_x and μ'_x are the mean values of the real and predicted data, respectively;

IV. CONTROL MODEL OF THE VENTILATION SYSTEM

Consider a ventilation system at the building level controlled by the logic diagram shown in Figure 2. This system operates at a certain percentage of the total capacity, for example 75% or 100%. All possible states of control are noted as, S_i, $i \in \{1, ..., n\}$ where n is the maximum number of states for the ventilation system. Also considered is that the comfort level is jointly influenced by relative humidity (RH), temperature (T) and carbon dioxide concentration, (CO_2), $< T, RH, CO_2 >$. The maximum bundles of comfort is given by the superior limit of the parameters, such as $< max(T), max(RH), max(CO_2) >$. The general idea of the control scheme presented in Figure 2 is to continually allow the ventilation system to shift from state S to $S-1$, where it consumes less energy as long as the values for T, RH and CO_2 are found in a feasible space (given by the comfort limits). The control scheme in Figure 2 can be improved for proactive building operations by including a prediction method of parameters that define comfort (see Figure 3). This leads to a replacement of the decision blocks "Comfort Limit" and "Maximum Comfort" with Predicted Comfort limit" and respectively "Predicted Maximum Comfort". Ideally these profiles and control model can be used in DSI activities through actions such as energy efficiency, load shifting, valley filling or peak clipping. In Figure 3 illustrates conceptually two possible situations for grid support by ventilation system; the first scenario forms the basis of results analyses in our paper.

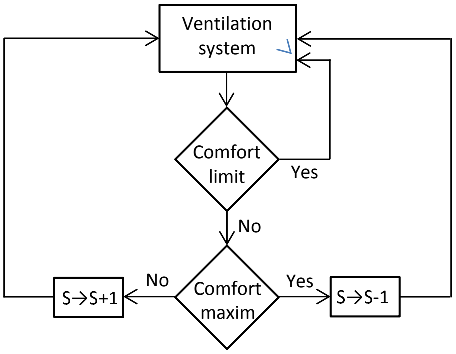

Fig. 2. Comfort profile during experimental day

V. RESULTS AND DISCUSSION

The results of the experiment are presented in sections V-A to V-B. Discussions follow in section V-C and V-D.

A. Energy performance

Figure 4 depicts power consumption for various electricity based comfort processes at the test building plotted during the day of experiment. Figure 4 depicts power consumption for various electricity based comfort processes at the test building plotted during the day of experiment. Ventilation system consumption is generally constant save for a few spikes and two troughs during reduction of nominal fan settings to 75%. For ventilation fan nominal settings of 75%, power consumption reduces by approximately $2kW$ below the modal consumption (see the reduction troughs in Figure 4 and 5). This demonstrate available building flexibility that can be tapped for grid support activities whenever possible.

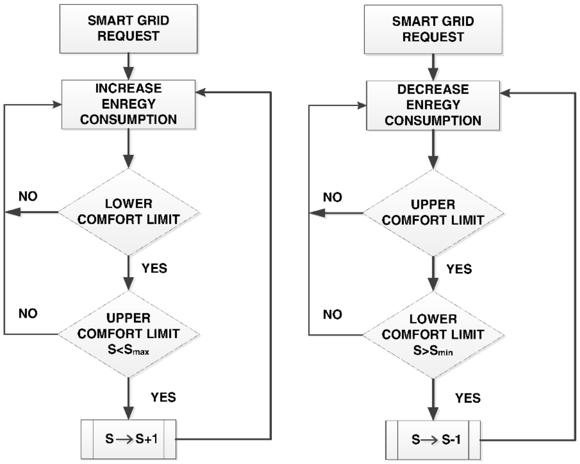

Fig. 3. Scenarios for deploying ventilation system for grid support activities Scenario (a): requirement for increase in energy consumption at building level; Scenario (b): requirement to decrease the energy consumption at building level.

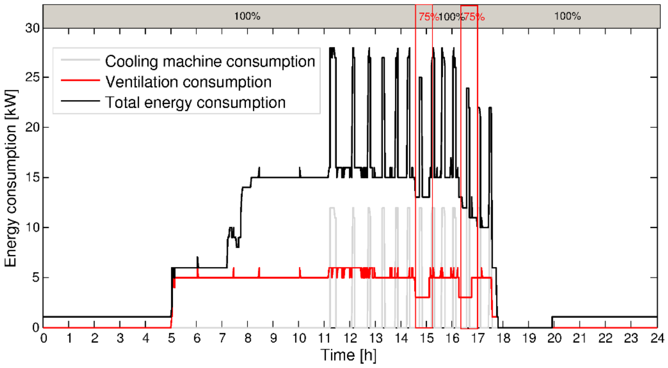

Fig. 4. Typical power consumption profile for electricity run comfort process subsystems show together with total energy consumption at the test building

B. Comfort profile

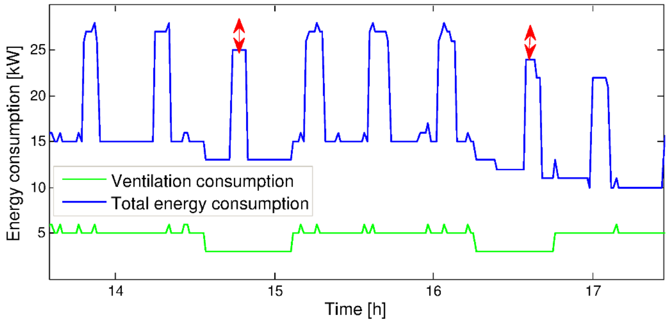

Fig. 5. Typical power consumption profile for electricity run comfort process subsystems show together with total energy consumption at the test building

TABLE I. GENERAL CHARACTERISTICS OF MEASURED COMFORT PARAMETERS

	Number of measurements		Mean (μ)		Standard deviation (σ^2)	
Nominal Vent. Settings	75%	100%	75%	100%	75%	100%
$T[C]$	88	914	23.9	22.4	0.67	1.19
$RH[\%]$	88	914	54.7	57.9	1.32	2.55
CO_2 [ppm]	88	914	537.2	516.3	9.99	46.05

TABLE II. RMSE AND R VALUES OF FORETASTED COMFORT PARAMETERS

	RMSE		R	
Nominal Vent. Settings	75%	100%	75%	100%
$T[C]$	2.49	0.37	0.78	0.98
$RH[\%]$	9.55	2.28	0.17	0.32
CO_2 [ppm]	2.89	0.93	537.2	0.91

Specific comfort values considered were T, RH and CO_2. Test experiment results had some missing values. We estimated the missing values by taking an average of the two values of neighbors. These were then plotted and examined whether T, RH and CO_2 are within comfort limits. Our results indicate that comfort conditions remained within the recommended of guidelines comfort for the Netherlands. Some comfort characteristics based on the gathered data, are detailed in Table I and Figure 6; ANN prediction as mentioned earlier on are presented in Table 2. A correlation factor close to 1 indicates a perfect correlation between the predicted and real values. It is noted that RMSE value of 23.12 for CO2 is a good achievement as it represents less than 5% deviation from the mean value of 537.2 ppm CO_2 obtained from test measurements. In the overall, investigating space comfort characteristics associated with the ventilation fan settings enables us gain insight on energy related flexibility for the building. This is important in formulation of framework for provision of services to the smart power grid. Such energy flexibility is depicted in Figure 4, see also representations in Table 1.

C. Energy and comfort balance

Grid support activities may be in the form of peak demand reduction (kW), peak shifts (in time-hours) and energy savings (kWh). In this case we seek to quantify the grid support potential by estimating the possible value of demand reduction (kW) and energy saving (kWh) when the buildings ventilation system operates at reduced nominal capacity.

At 75% nominal setting of the ventilation system for periods of up to 40 minutes, there is a reduction in peak demand by 2 kW; this translates to an overall energy savings of 1.34 kWh ($= 4800kJ$). Also, there appears to be no significant change in comfort during at 75% nominal setting of the ventilation fan for periods of up to 40 minutes; this is in specific reference to carbon dioxide concentration, relative humidity and room temperature. This is in line with findings from previous studies that suggest that additional building energy flexibility can be leveraged from the fact that a mismatch exists between code defined comfort ranges and prevailing comfort conditions in buildings [23]–[25], and that buildings are arguably over-designed [26], [27]. However, it must be taken into account that with extended duration of grid support service offered, building response time and penalties as a result of reduced comfort, productivity, health and safety, economic gains, wear and tear of building equipment and compensatory building operations mode required for the activities. Regarding productivity, surrogate studies have shown significant increase in performance with increased ventilation rates in buildings [28]–[30]. Minor deviations from these are allowable as long as they are for short periods (in most cases the period of service

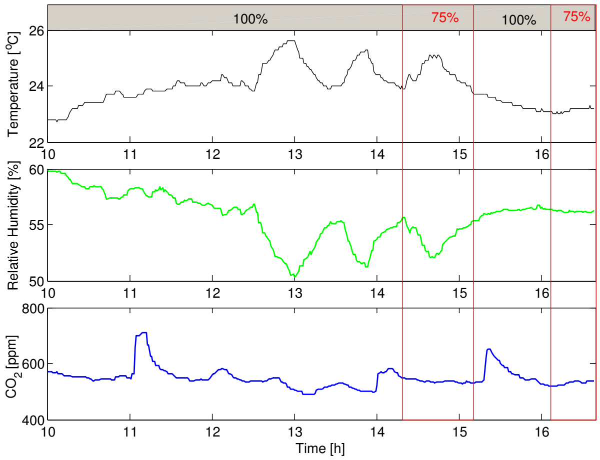

Fig. 6. Comfort profile during experimental day

rarely exceed 50 minutes for the EU countries), do not affect overall productivity greatly, and are justifiable economically. It is also acknowledged that our test results did not consider below operational and comfort characteristics:

- Concentration of carbon dioxide increases with occupants population; approximately 350 ppm above the outside levels is considered a good surrogate for comfortable ventilation [31].
- ventilation rates below $10l/s$ per person are associated with a significant prevalence of perceived air quality; on the other hand building codes specification is $2.5l/s$ per person [31].
- high ambient temperatures would increase the size of indoor cooling load. For constant air volume ventilation system this also implies that reduced ventilation capacity would lead to reduced cooling rate; eventually the system may take longer to reduce operational temperature
- absence of night ventilation will result to greater load plasticity and hence deny opportunity for peak shifting.
- extended period of operations at reduced nominal capacity imply greater plasticity and loads cannot be reprogrammed further for added energy advantage.

D. Responsiveness

Key components of grid support services in a DSI framework are: control devises, communication linkages and a database system. Effective coordination and integration of services between the two divides of power supply system (building side & power grid/utility side) is reliant on an equally effective control, and robust information and communication infrastructure [11]. Controllability and responsiveness are thus key in grid support services. These terms are closely linked with controllability being used to refer to the portion of load installed in building (expressed as a % of total) that can be effectively deployed for grid support activities [32]. Responsiveness for a demand resource on the other hand refers to its inherent ability to react to power system requirements with a view to maintaining or improving reliability [6]. Critical parameters for responsiveness are therefore time bound and include time for demand shift, data and information latency, data transfer rate and range. Time for demand shift is dependent on the type of grid support activity at play and the market; for example in the in the Netherlands this could be in terms of immediate deployment and full availability for a span of at least 15 minutes when dealing with secondary reserve [33]. For building load deployment for grid support activities, data and information latency of 5 seconds and transfer rate of 50 $Mbps$ are ideal [34], [35]. Three main controllability models exist for building-grids interactions. These are [6], [7]: 1) Master-Slave Control: In this case control responsibility is shifted to grid control centre and building loads follow the grid command. This is the current norm but is challenging because of the fact that coordination of high number of loads is cumbersome and expensive due to required additional investment in individual load functional monitoring. This is paramount in the legacy power system whereby the grid takes full control of appliances. 2) Hierarchical Control: For this framework, individual loads, buildings and neighbourhoods may be hierarchically controlled as virtual power plants with ability to dynamically update power availability status and interface to the next hierarchical control level. Hierarchical control may however lead to higher information latency and delay in response time when ill designed. This is the common framework for DSM test beds. 3) Distributed Control: In distributed control, decision making at localised levels is emphasised. In this case, buildings may have greater role in decision making on participation in grid support services. However, the disadvantage of this lies in the fact that it may results to: information overload, slow response times associated with management of various decision nodes, conflict amongst local controllers or either over-supply or under-supply of grid support services. This can be sorted out using reliable information aggregation and exchange. This is the idealised control for DSI.

Due to strict requirement in terms of response time and availability period, provision of grid support service by buildings need control strategies that are speedy with very low information latency [4], [6]. Droop based frequency control for various load groups may thus be preferable; this approach uses net frequency deviations from established reference to distribute load changes across systems in stable manner [7]. Also crucial in the reduction of information latency is event coordination framework. Two approaches dominate in building-grid interactive service and event coordination [28]: push and pull modes. In push mode grid control centre initiates communications by sending signals for power reliability grid support to building energy management systems whereas in pull mode building energy management systems periodically polls the grid control centres power reliability status for any support requirement. From indoor comfort management perspective it is logical to maintain full operational control at building level hence pull mode becomes preferable. However, pull mode is associated with longer information latency which may hamper response time for grid support [10].

VI. CONCLUSION

Building systems are designed for near peak operation which occur only for a short period. For this case study, it has been demonstrated that that for a ventilation fan with 15000 m3/h capacity, operations at 75% nominal setting for 40 minutes duration would yield approximately $2kW$ peak power reduction without significantly breaching ventilation comfort boundaries (that is over 30% of ventilation power reduction). This translates to an overall peak energy reductions of $1.34kWh$ (this is, approximately $0.8Wh/m^2$). On its own this amount of energy savings may not be significant; however, it becomes highly significant for a federated system of loads (for example, taken that the total office space in the Netherlands is 46 million m^2, significant peak energy reductions can be achieved). Use of hierarchical control framework is farvoured to achieve desired controllability mainly because of its ability for reliable coordination whilst also achieving measured level of decentralised control. However our study did not fully quantify the following: 1) cost effectiveness of grid support services provision using installed ventilation systems at building level, and 2) response time for ventilation system in event of deployment as to support grid activities.

It is recommended that longer tests be conducted at reduced nominal capacity to establish these with certainty. Also recommended is addition of other test variables such as duct pressure, draught and comprehensive occupancy in the building.

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