Comfort demand leading the optimization of energy supply from the Smart Grid

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Abstract

The Smart Grid is being developed to cope with fluctuations in energy generation from different energy sources. To better match energy demand and energy supply and to achieve improved overall efficiency, the process control of the energy infrastructure within buildings also needs to become smart. Therefore it is necessary to measure and develop new control strategies for the major energy consumers like Air Handlings Unit of the Heating Ventilation and Air Conditioning system with its ventilators. This process control of the energy demand on building level must be in the future in interaction with the energy supply by the Smart Grid as well as the outdoor environment (solar energy and outside temperature), but under strict conditions for a healthy and comfortable indoor environment. In the last year experiments were conducted in an office building to get insight into different process control strategies in Building Energy Management Systems that incorporate Smart Grid interaction and offers possibilities for energy reduction while maintaining the required comfort of occupants. Initial results are presented regarding control strategies which are flexible enough to cope with the dynamic demands from the user and at the same time allow the use of economic benefits of the Smart Grid.

Keywords; Smart grid, energy management, BEMS.

INTRODUCTION

In Europe the built environment accounts for nearly 40% of the total energy use (EIA 2011). Most of this energy (nearly 87% for non-residential) is used for building systems with the goal of providing comfort for the building occupants (Opstelten et al 2007). Due to unintended use and inadequate building management, 85% of buildings do not function properly (Elkhuizen and Rooijackers 2008). Energy use in the built environment can be reduced by improved building design and energy management during lifecycle without compromising the desired indoor comfort of the users. Energy management is necessary to reduce energy usage and optimize supply. This can be achieved by integrated management of energy flows in buildings (Kyung et al 2011(Georgievski et al 2011). It is important to look at the energy demand and the interaction with the energy grid, integrating the communications with the building systems in and around the building, while keeping occupants comfort primodal. Recent initiatives to upgrade the existing power grid to the so called ‘Smart Grid’ (SG) requires a transition in the distribution part of the grid: turning it from a passive system into an active system. A key characteristic of the smart grid is its multi-directional flow of power and information and hence transformation of the demand side management to demand side integration philosophy at low level voltage. The local generated energy can be in mismatch between demand and supply resulting in the desired increase of buffer capacity(Sapurto et al. 2012). Mostly in the case of heat, storage is less of a problem compared to electrical energy. In most cases the surplus in electrical generated energy is fed back to the grid. This development introduces a new challenge for the grid, namely, possible changing energy flow direction at lower grid levels due to the feed in of renewable generated electrical energy (Slootweg et al., 2011). This implies that building must also provide service to the electrical smart grid in as much as it is also serviced by the later.

Current grid management maintains balance by increasing or decreasing centralised power generation based on demand side behaviour or requirements. With the expected increase of renewable generated energy in the total generated energy mix, this introduces a stochastic behaviour, which necessitates for a change in the the management of the grid

Slootweg et al., 2011 statedthe increase in decentralised active loads such as, micro Combined Heat and Power (µCHP), Electrical-vehicles, heat pumps which can participate in the energy management and possibly react on grid requests or economic stimulations, compared to the passive loads connected to the grid can be a solution for future grid management. Active loads can request or in some cases even deliver energy to the grid and schedule their demand or even change their characteristics online.

In order to compensate active loads, there has to be an economic compensation. A classic example of economic stimulation is the double tariff structure, evoking households to shift their energy use to economic stimulated period which is the most convenient period for the grid. For now the more flexible tariff structures are still in experimental phase. The mix of connected active and passive loads will keep changing in future even as the mix of electricity generators. The Smart Grid (SG) is required to be the solution to all mentioned possible challenges managing electrical energy production, distribution, buffering, and consumption matching supply and demand making use of the available system flexibilities (Slootweg et al. 2011). Grid management, control, voltage management, power quality, and the need to modify the system security will change due to all mentioned development. New policies and contracting with flexible tariff structures are possibilities which are being investigated.

The SG incorporates current physical electrical grid infrastructure integrated with Information and Communications Technology (ICT) in grid components, and a communication network to enable energy management. (Wang et al., 2011) The real 'Smartness' of the SG is integration of multiple functionalities to guarantee properties including; reliability, availability, stability, controllability, and security, and at the same time realise overall system optimisation. Functionalities boil down to energy management making use of the flexibilities of all grid elements connected. The purpose of energy management measures, should be to compensate surpluses and deficits in the network. Flexibility is the degree to which the pattern of consumption and generation can be influenced. In the systems view, this will lead to a better balanced and controlled network at all levels (Acevedo and Molinas 2012, Lo and Ansari 2011, Dave et al. 2011, Lopes et al. 2011).

In offices Building Management Systems (BMS), also known as Building Automation Systems (BAS), controls the HVAC systems to facilitate building operation. These BMS evolved over time with the addition of more and more systems, functionalities, and requirements. BMS with energy use reduction during life time as an extra goal, turned into Building Energy Management Systems (BEMS) (Choi et al. 2011) and (Han et al. 2011). The main goal of the BEMS is to fulfil the occupant comfort requirements while reducing energy consumption during building operations (Yang and Wang, 2011). The BEMS uses peak shaving and load shifting based on planning to reduce the energy consumption together with energy efficiency improvements of systems equipment and energy management strategies.

METHODOLOGY

To study the possibilities and restrictions using a Building Energy Management System(BEMS) for the information exchange between building and Smart Grid, a middle-out approach was chosen. This middle-out approach is from the interface towards the SG and towards the BEMS and focuses on the communication and interaction between the SG and the BEMS. This approach also deals with the actual comfort and energy demands of the user and optimization of the energy flows. In the process the user has the leading role by setting the desired inside climate conditions.

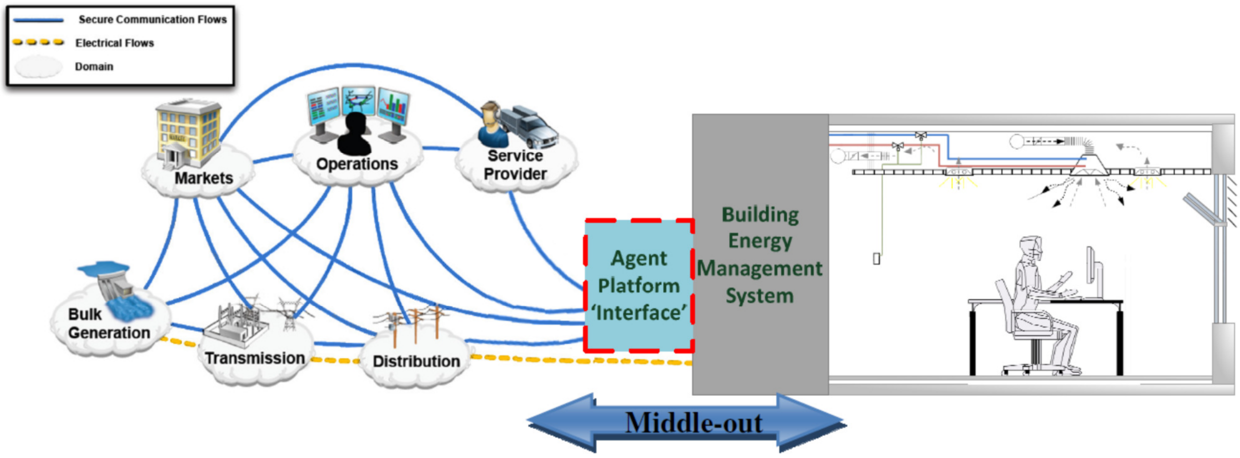

Figure 1: Middle-out approach from interface to building and Built Environment level.

The energy demand of buildings is related to the physics of the building, the environmental climate, and significantly to the specific control scenario for indoor environment and building operations. According to Robinson et al (2011) there has been no attemptto develop a general model predicting the probability of switching on or off the range of HVAC equipment, together with occupants' desired set point temperature, and how these choices depend on the range of key environmental stimuli. In addition, user's preferences are considered as a vital factor in deriving the appropriate control strategy (Yang and Wang 2011) .

The building systems control strategy rely on code defined occupant comfort ranges (Klein et al 2012) and operate according to fixed schedules and a constant occupancy. This is inefficient in their energy usage for maintaining occupant comfort as they do not in-cooperate the effects of real occupant behaviour. Li et al (2012) identify a number of control strategies based on accurate building occupancy:

- Lower temperature demands in unoccupied areas. Zhang et al (2009) concluded that building energy reductions can be obtained when temperature was lower in winter period and higher in summer period;
- Maintaining lower ventilation rates in unoccupied areas; leading to less ventilation losses and building energy needed;
- Supplying airflow based on occupancy; two researches (Yang et al 2011; Sun et al., 2011) looked at dynamic airflows based on the CO_2 concentrations. Applying these strategies savings could be achieved of 15% to 56% found by Sun on the ventilation energy;
- Responding to dynamic heat loads on a timely manner; if a change of the occupancy is detected in real time, associated changes of internal heat loads can be calculated, HVAC systems can respond to these changes immediately, before the temperature varies to an extent that is detectable by thermostats.

For evaluating the effects of power management on thermal comfort and IAQ a case study building was used, a typical Dutch office building was selected for the experiments. Before starting the experiments, the building was analyzed and prepared for the experiments. This so called 'zero measurement' is used to identify aberrations in the building operation. The results of the test will also serve as reference for the experiments. After this it was experimented with different energy management scenarios to reduce building systems energy demand as service to the Smart Grid. An experiment to reduce the air-flow of the constant volume air handling unit system while staying within the comfort and IAQ boundary conditions are presented in this paper. The initial and reduced air-flow were measured together with the corresponding CO2 concentration and energy use with the goal to identify when and to what extent it was acceptable to reduce the air-flow.

The Case Study Office Building

The Office was built in 1992 and revised in 2009. It is a three story high building. Building characteristics:

- 3 floors;
- +/- 1400 m² floor space;
- +/- 48 fixed employees;
- 59 office desks;
- windows can be opened;
- solar shading devices;
- mainly shallow plan;
- office hours between: 7:00 and 18:00;
- working days: Monday – Friday.

Figure 2: Test case office building Kropman Breda.

The characteristics of the technical building equipment are:

- mechanical ventilation system;
- air handling unit of 15.000 m³/hour;
- heat recovery wheel (no recirculation of air);
- central cooling by three air supply group after coolers;
- central heating by air and two radiator groups;
- electrical steam humidifier.

The first floor was chosen for more detailed measurements because all the supply system groups were situated on the first floor (Figure), and the first floor was the most regularly occupied floor. Measurements used by the BMS to maintain a comfortable indoor environment were the outside temperature and the inside temperature of two rooms at the first floor. Positions of both measurements were indicated in the floor plan, see Fig. 3. In order to evaluate the indoor climate, additional measurements were done in the rooms on floor one. In each room the temperature, CO2

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concentration, humidity and average airspeeds were measured during the project. The measurements were done in accordance to ISO 7726 (ISO, 1998) and the ASHRAE Performance Measurement Protocol (ASHRAE, 2010).

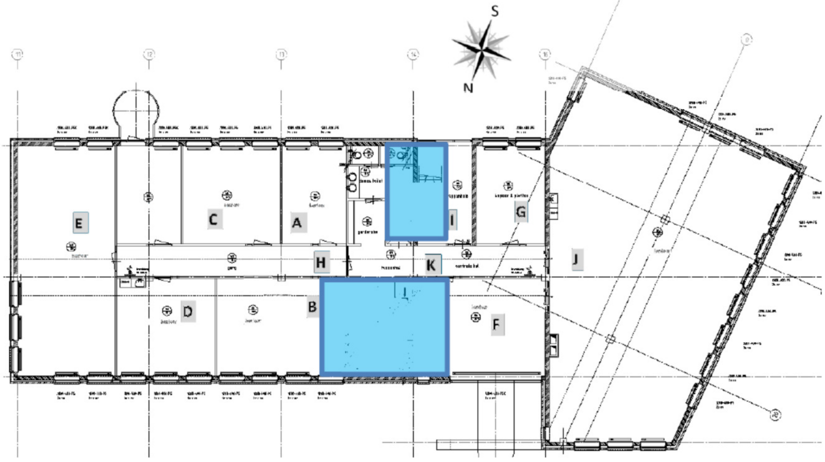

Figure 3: Floor plan first floor test case office building Kropman Breda

Room A has the external wall orientated on the south and is setup as a one person work
room. Room B has an external wall orientated on the north and is setup with multiple workplaces. During the measurement period a maximum of three people were present in the room while most of the measurement period not all of them worked simultaneous in the room due to holidays.

The office building is connected to a mid-voltage transformer stationIn the building the two main connections and main power systems connected were measured. Fig. 4 below illustrates major electricity load groups of the office building.

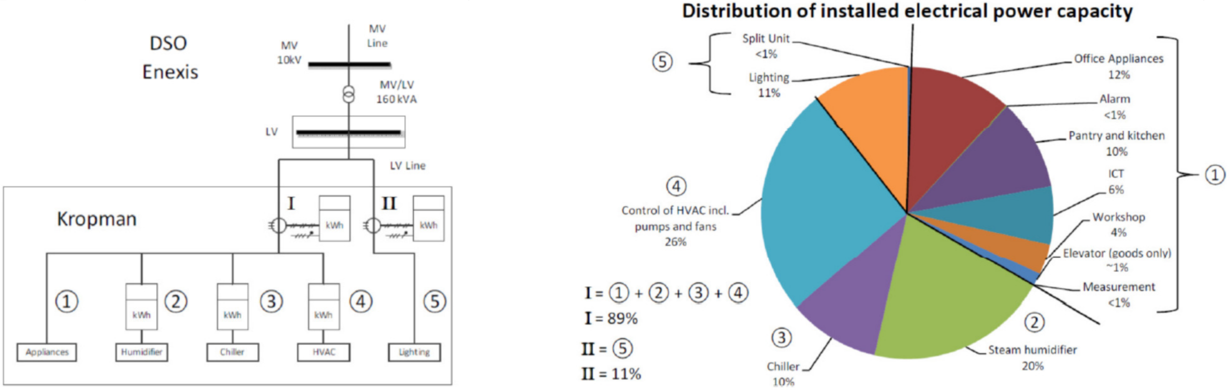

Figure 4: Abstract representation of the electrical connections from Mid Voltage grid to building and Figure 5. Distribution of installed electrical power capacity.

The distribution of installed electrical power capacities for both groups is presented in Fig. 5.. Notice the installed electrical power capacity for lighting is about 11% of the total. While the other power connection covers about 89% of the installed capacity. The HVAC control unit, controls the building systems by sending the control signals, supplies the electrical power to the fans and pumps, and facilitates the communication signals to the BAS and all connected components. In order to evaluate the characteristics of the energy use of the installed systems measurements were done:

- Main supply electrical energy measurements; main supply power group; main supply lighting group;
- Sub supply electrical energy measurements; electrical energy chiller; supply electrical energy humidifier; electrical energy systems control;
- Electrical energy use of lighting equipment; TL lighting of 7 rooms on the first floor; 2 down lighters of the two hallway on the first floor;
- Electrical energy use of appliances in 7 rooms; Personal Computers; laptops; laptop docking stations; monitors; small printers; phone chargers; water boiler; split unit;

RESULTS

Overall energy use

All the presented energy use profiles together form the total energy use profile as presented in Figure 6. Continuous main base load of the office building was approximately about 4 kWh/h represented in dark-blue (A Fig. 6). The maximum power use measured by the main connections I + II during the project was 36 kWh/h, represented in red (B Fig. 6). The main energy use profile during the day looks quite stable (C) while some profile of appliances can be clearly seen in the total profile. The early start scenarios are indicated in figure 6DThe Energy use profile of the Chiller isalso clearly visible (E) in Fig. 6.

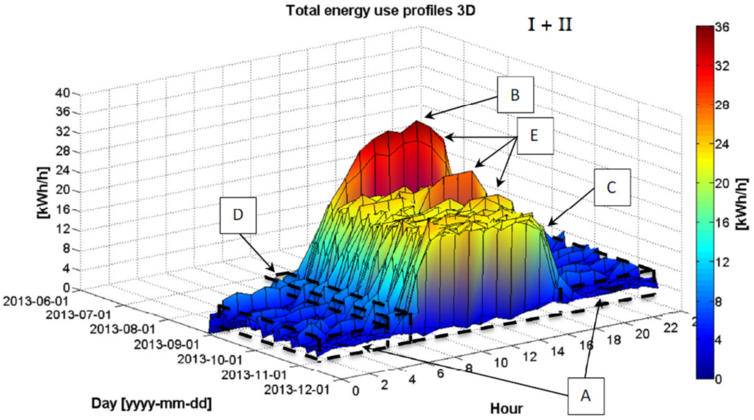

Figure 6:Total energy use profiles stacked by date.

Energy efficiency scenarios for the HVAC, lighting, and remaining have the biggest potential since the energy use of these groups are main components of the total consumption. Energy consumption by the chiller and humidifier are more dependent on the weather conditions and on the time of year:. Even with the chiller active (week 36), see Fig. 7, the lighting and remaining consist each of 30 % of the total energy consumption. Compared to the ratio of the installed capacities, see Fig. 5, where lighting only consists of 11% of the total installed capacity, the energy consumption of the lighting also has relative big share.

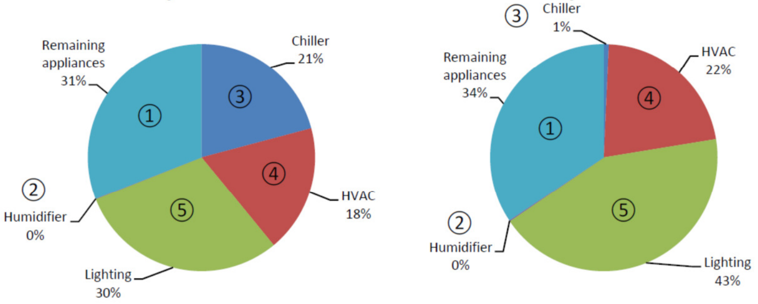

Figure 7:Total energy consumption for calendar week 36 and 42 divided by main appliances.

HVAC Air Handlings Unit

Fig. 8 shows two different energy profiles for the HVAC control unit, the left profile consists of Monday morning early start setting, and the right shows the profile with active night ventilation.

As can be seen from this figure, the maximum energy use by the system is 6 kWh and minimum is 0 kWh.

In the right figure, the energy use by night ventilation can clearly be seen due to the energy use from 0:00 hr. till 6:00 hr. The energy consumption due to night ventilation was maximum 5 kWh. This gives an insight in the amount of energy use by the fans compared to the other components powered by the HVAC control unit. In Fig. 8 block A represents the night ventilation. Block B represents the normal start-up profile and block C the normal day ventilation profile. The left figure shows an early start, block D, as the clock program lets the building systems start up earlier on Monday morning.

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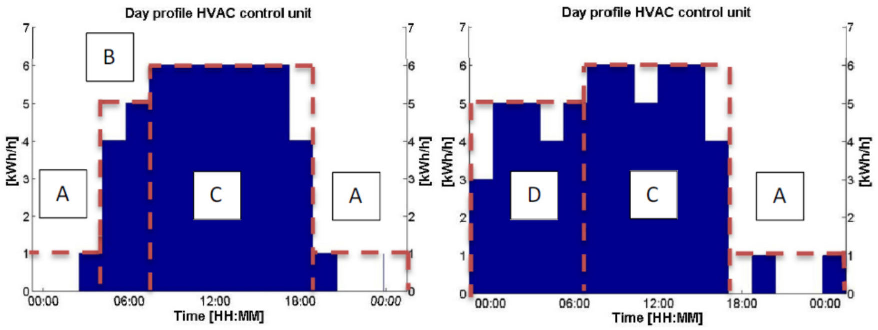

Figure 8: Energy use day profiles of the HVAC control unit, left early start (Monday), right active night ventilation.

Fig. 9 presents the energy profiles for each day in a 3D plot. Here the energy profile with night ventilation versus the normal day profile can be seen more clear. The energy use is given a colour where red presents the maximum use of 6kWh/h.

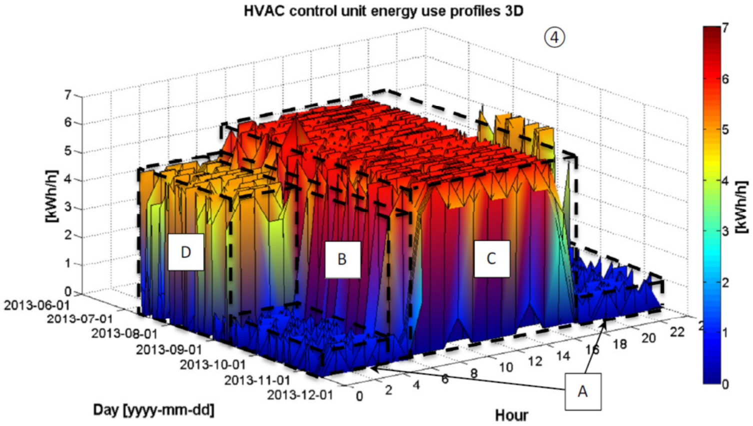

Figure 9: HVAC control unit energy use profiles stacked by date.

Experiment: Fan power reduction

The ventilation supply is divided into 3 groups respectively; north, south and the drawing room. The building is mechanically ventilated by a central AHU with a steam humidifier and heat recovery wheel. The air is supplied and extracted through the ceiling in the different rooms. The main task for the ventilation system is supplying fresh air for a healthy work environment; the humidity content during winter is set at 8.0 (g/kg), for a temperature of 21.5 (˚C) this results in a RH of 51%. The fresh air is controlled by valves and supplied- as well as extracted by fans, the heat is recovered by a heat recovery wheel. The operating components of the AHU requires real time data, so sensors are installed for the humidity, duct pressure and temperature.. The pressure in the intake duct is controlled by an RPM (rotations per minute) controller connected to the supply fan. This is PI-D-controlled, based on the desired and measured pressure in the supply duct.

Table 1: Control strategies supply- and exhaust fan

Event:	*Variable parameter:*
Supply fan	250 [Pa]
Exhaust fan	Control supply fan – 5% offset
Time interval adaptions fan speed	00:30 [mm:ss]
PI-D automatically controlled	20 – 100 [%]
Fan stops, belt breakage	10 [Pa]
Fan stops, dirty filter	280 [Pa]

An overview of the Air Handling Unit and its components is shown below. The biggest energy consumers during winter time were the humidifier, supply fan and exhaust fan. During summer the cooling machine is also a large energy consumer, but is not taken into account, because this study aims the AHU analysis during autumn/winter time when no significant cooling is needed. In this experiment we looked at the reduction of the air supply and exhaust.

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The supply and exhaust fans have a maximum rated power of 5.5 and 4.0 (kW) respectively. The control is set according to the pressure at the supply duct, namely 250 (Pa), 1200 RPM. The fans consumes about 5 (kW) during this normal operation and The PI-D control value, is automatically set to ±0.80. Table 2 shows the settings of the experiment. Between these intervals there is at least 1 hour 'normal set point' and the timeframe is given in Table 3.

Table 2: Fan reduction experiment

Interval time:	*Supply and exhaust fan*
15 minutes	25% supply reduction (PI-D control value 0.60)
30 minutes	25% supply reduction (PI-D control value 0.60)
60 minutes	25% supply reduction (PI-D control value 0.60)

Table 3: Short time adaptions supply & exhaust fans

Interval time I	15 minutes
Return to normal setpoint	60 minutes
Interval time II	30 minutes
Return to normal setpoint	60 minutes
Interval time III	60minutes
Total experimental period:	3 hours and 45 minutes

The energy use of the fans was monitored to determine how much energy could be saved by reducing the fans speed by 25% while keeping the carbon dioxide concentration within the set comfort boundary conditions.

Results of the experiment

The PI-D control value in the BMS was maximized from unlimited to 0.60 to reach 25% with reductions at time intervals I, II and III. Before start of the experiment, the following settings were found from the AHU, BMS: PI-D automatically at 0.80 ~ 0.81; Supply fan 1210 RPM; 250 (Pa) at supply duct; Exhaust fan 1072 RPM

The control value of the fan was reduced to 0.60, for achieving 25% fan reduction. This resulted in the following settings: Supply fan 900 RPM; 142 (Pa) at supply duct; Exhaust fan 767 RPM. Carbon dioxide concentration and relative humidity are the most important climate parameters for analyzing the effect to the indoor environment during the experiment all are shown in Fig. 10 and Fig. 11.

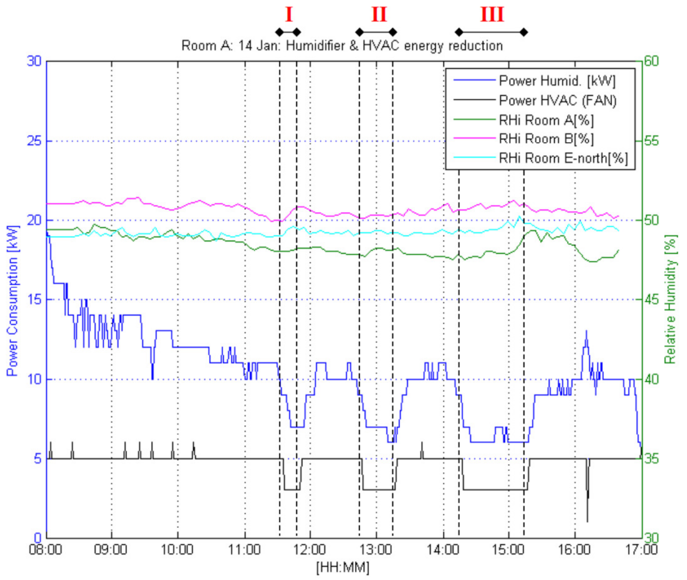


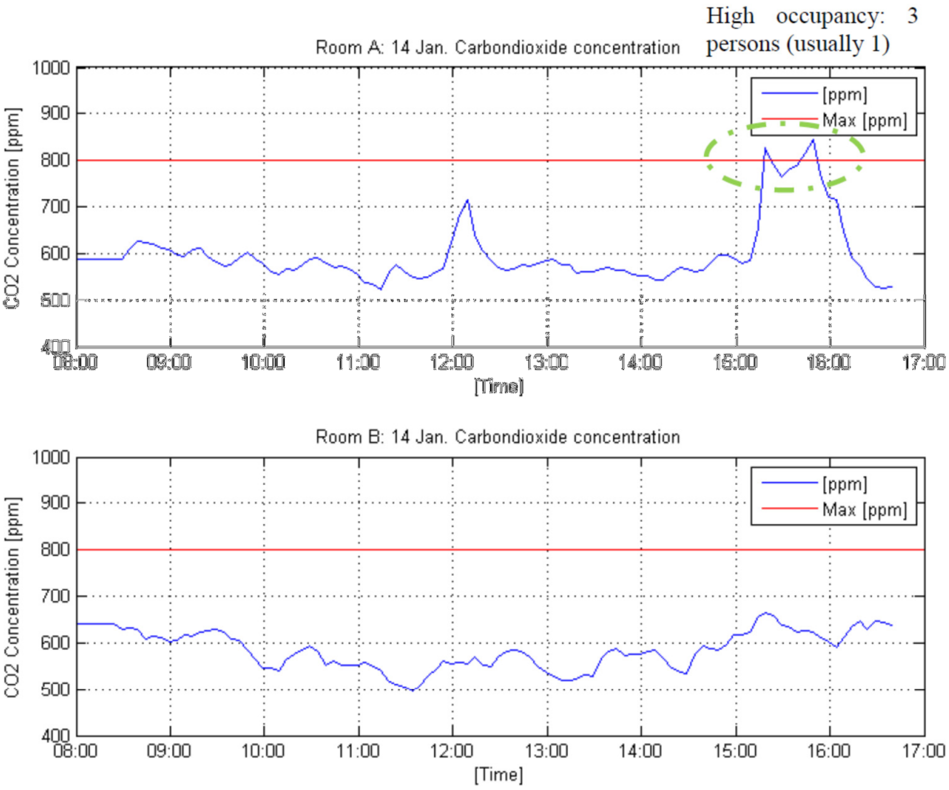
Figure 10: Energy consumption fans and humidifier during experiment II, interval times are black dashed

From Fig. 10 it can be concluded that a fan supply reduction of 25% also result in a decreased energy use. Another positive energy effect of this fan supply reduction is related to the humidifier power consumption. The energy consumption of the steam humidifier is also significantly reduced during interval time I, II and III, see Table 4.

Table 4: Power reduction during experiment II

	Power reduction fans	*Power reduction humidifier*	*Indoor RH*
Interval time I	± 2 kW	± 5 kW	Remains stable
Interval time II	± 2 kW	± 5 kW	Remains stable
Interval time III	± 2 kW	± 4 – 5 kW	Remains stable

The fans (RPM) almost immediately responded to the changed (PI-D) control value. Compared to a normal day, energy was saved during and slightly after the interval times because of the response time of the humidifier. The RH indoor remained stable at about 50 (%), compared to a day in December when the humidifier also did operate.
The CO2 concentration was recorded during the experiment and shown in Fig. 11.


High occupancy: 3 persons (usually 1)

Room A: 14 Jan. Carbondioxide concentration

Room B: 14 Jan. Carbondioxide concentration

Figure 11: CO_2 concentration during experiment II for Room A & B

Interval time I (11:33 – 11.48)
During this first time interval, an extra energy reduction from the steam humidifier resulted in total saved energy during this interval of approximately 7 (kW). This value differs because of the high fluctuating energy demand of the steam humidifier. The absolute humidity instantly increased to 8.6 (g/kg) at the moment that the fans were reduced. This is explained by the fact that the flow rate was decreased, so the same steam input resulted in higher humidity levels in the supplied air. This event caused energy reduction for the steam humidifier, since less flow required less steam to fulfill the required vapor demand (or set point). During this interval, the occupancy in Room A was 1 person and in Room B 2 persons. Doors to the corridor were opened. The carbon dioxide concentration in Room A remained stable and in Room B it was slightly increased, but within set comfort boundaries.

Interval time II (12:45 – 13:15)
During this second time interval, approximately the same energy savings (as interval time I) occurred. At the time of the fan speed reduction, the measured absolute humidity instantly rose to 8.7 (g/kg).

In room A nobody was present and in room B at start also nobody was present and at the end of interval time II: 1 person was present. The CO2 concentration in room A decreased from 567 to 559 (ppm). In room B; the CO2 concentration decreased from 583 to 523 (ppm)

Interval time III (14:15 – 15:15);
During this interval about 6 – 7 (kW) power was reduced, at the time of reducing the fan speeds, measured absolute humidity instantly rises to 8.5 (g/kg). The CO2 in room A ranged between 557 to 657 (ppm). 5 minutes after this period (15:19h) a concentration of 828 (ppm) was measured. The CO_2 concentration did not exceed the set comfort limit of 800 (ppm) during experimental time (11:33h – 15:15h). The concentration did increase from the end of the experimental time interval III this was because the relatively small room A was occupied with 3 persons. These higher concentration was maintained for 40 minutes even when the fans were already on normal set point. This can be explained by the occupancy in this small room at the time. The CO_2 in room B rangedbetween545 – 656 (ppm), a small concentration reduction from the start and then an increase. The occupancy in this room started with one person and later on with a second person.

DISCUSSION AND CONCLUSIONS

The shift towards smart electrical grid cannot ignore connected buildings. This implies active participation of buildings in the grid. Energy management in the Micro Grid, the electrical infrastructure directly around buildings, depends highly on the energy management inside the buildings, called the Nano Grid. In this study, with respect to the Micro Grid within the Smart Grid, the network and electrical energy consuming systems in the building managed by the BEMS were called Nano Grid.

For an optimal SG from a system of systems point of view, the BEMS has to be coupled with the management platform of the grid (Dave et al., 2011). The control of loads in the building, may also be a resource to the grid using the flexibilities in service of the grid in Demand Side Management (DSM) scenarios as so called Demand Response (DR) or Load Control (LC). (Callaway and Hiskens 2011) However, these flexibilities remain largely undefined with respect to interactions with the power grid. Also, the development of the Smart Grid is still at an early stage and some parameters are yet to be fully defined with respect to interactions with NanoGrid.

With the development of a communication platform between the BEMS and Grid Energy Management System (GEMS) both systems get more interconnected and thus more dependent on each other. The present choices made in energy management have the capacity to, affect future choices. (Callaway and Hiskens 2011) This means goals and functionalities of both coupled energy management systems have the potential to effect each other.

For the built environment, now is the chance to prepare for the coming SG. New strategies of energy management, building management, and comfort management have to be developed to anticipate on the coming possible changes on Demand Side Management by Demand Response (DR) and Load Control (LC).

This study is a first step towards the evaluation of the possibilities for adapting the consumption patterns of an office building and the impact of energy management with grid interaction. Here the focus was on the air handlings unit and the amount of supply air. Air-flow reduction can be used as a service to the grid or energy efficiency measure, with a power of 2 kW. Beside the direct energy use reduction of the air handling unit fans the cooling demand reduces with 22%. Reduction of the airflow can be used almost during the entire year maintaining acceptable CO_2 concentrations.
In future research the effects of other interventions in relation to lighting and cooling will
be studied to get an overall insight of the possibilities of reducing the energy demand of the building as a service to the Smart Grid.

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