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Energy analysis of net zero energy buildings: a case study

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The building sector is a significant contributor to global energy usage and environmental emissions. Advanced building design, optimal selection and sizing of building components, and energy efficient operation are among the key ways of significantly reducing overall building energy demand. Achieving reduction in energy demand is a key directive of the net zero energy building concept. Building designs dedicated to meeting net zero energy building requirements are becoming more commonplace as a path towards reducing the overall emissions from the built environment. This work analyses the energy demand of a net zero energy office building and compares it with a more standard commercial building design. Through analysis of energy use, the effectiveness of energy efficiency measures incorporated in the net zero energy building are evaluated and results provided.

Keywords
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Heiselberg, Per Kvols

Energy Analysis of Net Zero Energy Buildings: A Case Study

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Abstract
The building sector is a significant contributor to global energy usage and environmental emissions. Advanced building design, optimal selection and sizing of building components, and energy efficient operation are among the key ways of significantly reducing overall building energy demand. Achieving reduction in energy demand is a key directive of the net zero energy building concept. Building designs dedicated to meeting net zero energy building requirements are becoming more commonplace as a path towards reducing the overall emissions from the built environment. This work analyses the energy demand of a net zero energy office building and compares it with a more standard commercial building design. Through analysis of energy use, the effectiveness of energy efficiency measures incorporated in the net zero energy building are evaluated and results provided.

Keywords - Net zero energy buildings; HVAC design; energy analysis

1. Introduction

The rapid escalation of energy use throughout the world over recent decades, driven by population growth and increased affluence amongst developed and developing countries alike, has resulted in the built environment consuming as much as 45% of primary energy use worldwide [1][2]. This makes the built environment the world's largest single contributor to overall energy consumption. With the burning of fossil fuels to provide energy having been identified as the major contributing factor to anthropogenic climate change [3], and electricity production in fossil fuel dominated countries such as Australia requiring over 3.1 units of primary energy for every 1.0 unit of electrical energy [4], significant ongoing effort to reduce the energy intensity of our buildings is required. By increasing the efficiency of building designs, including a mix of localised and grid based energy production, and introducing energy conservation strategies, a significant portion of the energy growth problem can be addressed [5][6].

In the Australian building sector, progressively tighter building codes have been successful to a degree in improving energy efficiency; however this improvement has not stopped the overall increase in energy consumption due to larger increases in floor areas and technology adoption [8]. Much of the energy used in existing commercial office buildings can be attributed to HVAC systems [9][10]. Significant energy use can also be credited to lighting, typically a quarter of overall energy use. Potential savings in HVAC and lighting systems come not only from new equipment and luminaire technology, but also improved building and occupant controls [11].

The concept of a net zero energy building (NZEB) combines the goals of energy efficiency and localised renewable energy production to create a building which meets all of its own energy demands, whilst ensuring a healthy and comfortable environment for its occupants [7]. A NZEB has an impact on both the demand side and supply side of the energy equation. Reducing energy demand is seen as essential in achieving net zero status as this reduces the required installed generating capacity. Energy demand can be reduced through a range of measures including but not limited to: installation of efficient appliances, lighting and mechanical systems; the passive design of a building to work with the climatic conditions of the site; behaviour change of occupants; and advanced control and optimisation.

A building with greatly reduced energy demands requires the sourcing of renewable energy on the supply side in order to be successfully net zero energy. Ideally this is supplied from renewable energy sources installed on site and within the building footprint. Some high density buildings have a high energy intensity compared with their building footprint. This makes on-site renewable generation difficult in many cases, even with dramatic and effective demand reduction programs in place. For this reason, off-site generation options – although less than ideal – are a viable solution to aid in achieving NZEB status [12]. The most commonly used and commercially feasible source of on-site renewable energy is solar photovoltaic (PV). Other sources of energy, such as wind are possible. Given the ubiquity and abundance of sunlight in most locations, the rapid simultaneous increase in performance, and decrease in cost of solar PV modules, achieving the NZEB goal has become more and more viable in recent years.

Future building design and control will be impacted by the changing dynamic of energy use in NZEBs. There is still much to be gained on how effectively building equipment and systems are controlled, as implemented in the Building Management System (BMS). Through the analysis of BMS data and that available from other sources, it is possible to gain an improved understanding into how a NZEB uses energy to meet its performance targets.

This paper presents the energy analysis of a case study office NZEB in preparation for meeting its NZEB certification requirements. Comparison to other energy efficient and typical modern commercial building designs is included in the analysis. Section 2 gives an introduction to the case study building including key energy efficient building elements and metering capabilities. Section 3 presents the energy analysis of the case study office building. Section 4 provides comparison to a conventional, modern commercial building, and Section 5 summaries the work presented.

2. Case Study Net Zero Energy Building

The case study building concerned in this study is the University of Wollongong's Sustainable Buildings Research Centre (SBRC) facility. The building is designed to target net zero energy performance, and is located within a coastal region of Australia at the University's Innovation Campus in Wollongong.

Fig. 1 Illustration of SBRC building conceptual design.

The building consists of a 2,600 m^2 double story research facility with two main wings on an 8,000 m^2 site (refer to Fig. 1). The first wing is a 1,700 m^2 building housing academic and open plan offices, education and training spaces, flexible laboratories, and a public exhibition centre. The second wing is a 900 m^2 high bay structure housing laboratory spaces and much of the energy efficient plant used in the building.

The SBRC achieves its high level of energy efficiency thanks to a range of design choices and cutting edge technology. The building is laid out in an H-shape with north-south orientation. This helps to optimise natural ventilation and maximises natural light throughout the building. A mixed-mode ventilation system utilizing a ground heat exchanger and in-slab hydronic system significantly reduces HVAC energy intensity compared to more conventional systems. Low energy lighting systems with intelligent controls are used where daylight levels are insufficient. PIR sensors detect if a room is occupied and photoelectric light sensors detect whether daylight levels are low enough to warrant the use of artificial lighting.

Solar PV arrays were installed on both north and south wings of the SBRC, providing a total capacity of 163 kW_p. The south wing rooftop holds most of the installed capacity with 120 kW_p, whilst 43 kW_p was installed on the north wing at inclinations of 30° and 70° to the horizontal. In addition to the conventional PV installed at the SBRC, an experimental array of Building Integrated Photovoltaic Thermal (BIPVT) panels has been installed. Ducts installed beneath the panels harvest the heat absorbed by the PV panels. As well as increasing the efficiency of the panels, the collected heat can be directed into the building for space heating if required.

Sub-metering points were installed at each generation and load connection to the main switchboard and renewable energy based building micro-grid. Additionally, each distribution board was divided into building services, general purpose, computer, and lighting loads, and metered separately. A single line diagram of the buildings electrical system is shown in Fig. 2.

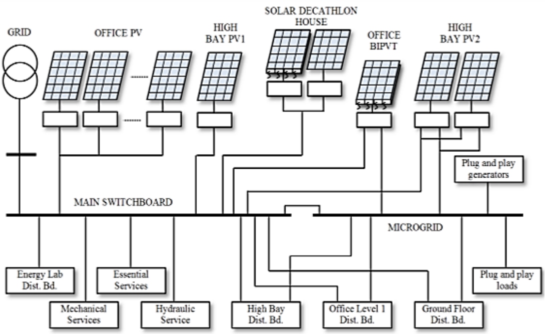

Fig. 2 Line diagram of SBRC electrical distribution system.

The HVAC system at the SBRC is able to operate in three modes – natural ventilation, heating, and cooling. Natural ventilation is implemented through the use of automated windows and louvres on the building envelope. It is designed to be the primary space conditioning mode for maintaining the building within the required thermal comfort, i.e. temperature set points of 20°C and 24°C. Outside of this comfort band, mechanical heating and cooling modes are used. The main mechanical plant equipment includes one air-source heat pump, two water-to-water heat pumps, three vertical and 12 horizontal ground heat exchangers, and six variable speed water pumps.

Ground-source heat exchange loops are used to exchange heat with the stable temperature of the ground. A variable speed header pump is fitted to the ground loop to maintain constant pressure to the system. Operation preference is given to the Ground Source Heat Pumps (GSHP) as they are more efficient over the air source heat pump, which is used only to meet the peak loads or in the event of GSHP equipment malfunction or servicing.

Low energy Virtual Desktop Infrastructure (VDI) was used at the SBRC instead of traditional separate PC terminals. Each desk has only a display monitor, keyboard and mouse with processing hardware located off site in a concentrated server configuration intended to achieve overall savings through economies of scale. A VDI terminal consumes around 8-20 W of energy compared to an average of 150 W for a traditional PC [13]. A VoIP phone system is used in place of traditional phone systems, further cutting down energy use.

The BMS of the building monitors and records a number of electrical meters every 15 minutes. This data is logged and can be accessed at any time from the BMS page. The key energy meters for data presented in this work include: the main incomer, northern PV array, southern PV array, combined mechanical services, and the BIPVT system. Energy meters were also installed on individual pieces of HVAC equipment such as heat pumps, fans, and water pumps. Provision is also made for future installations such as wind turbines, electric vehicle charging stations, and an experimental wind tunnel. These meters are capable of measuring active, reactive, and apparent power, as well as the current, voltage and frequency of all phases.

Additional metering of the solar arrays is possible through the online monitoring services provided by the solar installer. Energy production is logged at 5 minute intervals and can be broken up into contributions from the north and south arrays, and individual inverters. Monthly and yearly summaries are also prepared automatically.

3. NZEB Performance and Energy Analysis

Innovative design and various energy efficiency initiatives enabled the SBRC to target a low 60 kWh/m^2/year of energy consumption (before on-site generation was considered). The projected annual energy consumption established during the design phase for the entire building was 148 MWh/year with 52 MWh/year dedicated to research equipment, i.e. not related directly to building operation. On-site generation from the PV system was designed to deliver 197 MWh/year in order to meet the NZEB requirement.

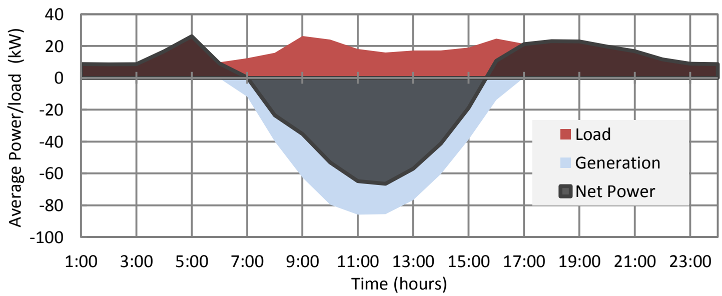

Fig. 3 SBRC Load/Generation in Average Winter Day.

The typical building loads and generation for an average winter day are shown in Fig. 3. This is an hour-by-hour average of the data throughout every day of July and August of 2015. The load profile demonstrates a typical morning peak while establishing building comfort levels, and a relatively flat profile throughout the day and into the evening (research staff and students tend to work reasonably late hours). Comparison of the shaded areas in Fig. 3 illustrates an example of the building meeting the net zero energy target on a daily basis.

Fig. 4 shows the energy consumption, generation, and net balance for each month of 2015 to illustrate the month-to-month behaviour of the building. Summer and spring months resulted in net positive energy production, averaging 13,000 kWh per month. This is due to the combination of these months providing the highest level of solar generation potential, and energy demand within the building being marginally lower than during winter – a result of more mild temperatures requiring less HVAC input. The net result during the winter and autumn months were also positive; however increased demand and lower solar yields resulted in an average net positive output of only 3,800 kWh per month.

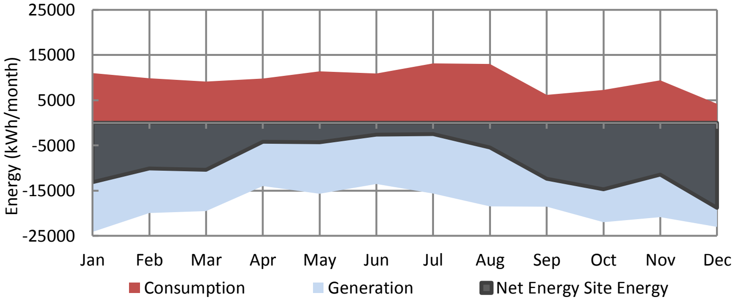

Fig. 4 SBRC monthly site energy balance in 2015.

The total generation for the year was 225 MWh – an average of 617 kWh per day, and above the design target. The total consumption was 115 MWh, averaging 316 kWh per day. This translates to an energy intensity of 44.3 kWh/m^2/year for 2015.

It must be noted that during 2015, the building did not operate at full occupancy capacity, nor were research labs fully fitted-out or utilised. It is expected that energy consumption would increase in the future for these reasons. It is important to determine what the energy balance picture will be at full operating capacity. To project this, energy consumption modelling provided by consultants during the design phase was used. The recorded generation figure for 2015 informed the other side of the equation. The consultants designed figure for consumption was 148 MWh – an additional 33 MWh on top of what was recorded in 2015. Assuming annual generation of 225 MWh, the resulted net positive balance will be 77 MWh.

The typical daily average lighting load profile for the SBRC building is shown in Fig. 5. It is interesting to note that the highest period of the consumption occurred after the office hours up until midnight. This is due to overnight security lighting which remained on at a low level in many parts of the building, later than normal working hours of building occupants, and external lighting. The observation that the highest consumption is outside normal working hours suggests that the building relies heavily on natural daylighting during office hours. Calculated lighting power density (LPD) for the case study NZEB was approximately 1.6 W/m^2.

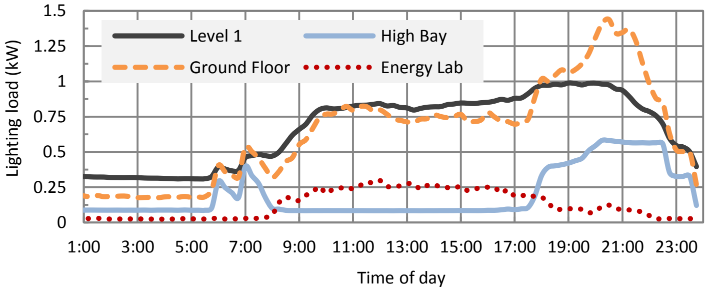

Fig. 5 SBRC lighting system average daily load profile

HVAC loads of the building in summer and winter months are compared in Fig. 6. The typical summer profile was taken from the averaged data throughout January and February of 2014, whilst winter data has been averaged from July and August of 2015. A significant increase in power consumption throughout the day in winter is observed when compared to the summer profile. It is clear that winter HVAC loads are larger overall, particularly at the start and end of the day, where solar thermal gains are lower and thus heating demand is higher. The large spike between 4:00am and 6:00am was due to the operation of the hydronic heating system. The winter HVAC load was reasonably consistent once comfort levels were established. More fluctuation in the summer and shoulder seasons HVAC load was evident with transition to and from natural ventilation modes.

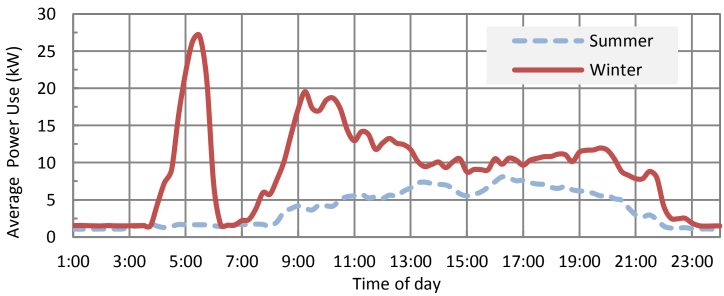

Fig. 6 SBRC HVAC loads in summer and winter average day.

4. Performance Comparison of Case Study Net Zero Energy Building with a Commercial Building

Enterprise 1, also located at the University's Innovation Campus is a three story commercial office building with a total floor size of approximately 10,000 m^2 and has been operating since 2011. The building consists of a concrete framed shell with lightweight curtain wall cladding.

Operable slatted timber louvres provide shade at the east and west ends when needed. Occupancy controls on office lighting systems aim to reduce unnecessary lighting use, as well as in bathroom areas where lights are switched off after a 1 hour period with no detection. Low energy compact fluorescent downlights are used, along with T5 linear fluorescent fittings in offices. This gives a resulting overall lighting power density of 8 W/m^2.

The base building was designed to achieve a minimum 4.5 star NABERS rating. A base-building rating concerns the greenhouse gas emissions associated with energy consumed by core building services such as common area lighting, lifts, HVAC central plant (not including supplementary HVAC used by tenants), and exterior lighting. It does not consider energy consumed by tenancy activities. The 4.5 star base-building means the building can be considered as state-of-the-art for a building of its type and one which is a good candidate to be compared against NZEBs.

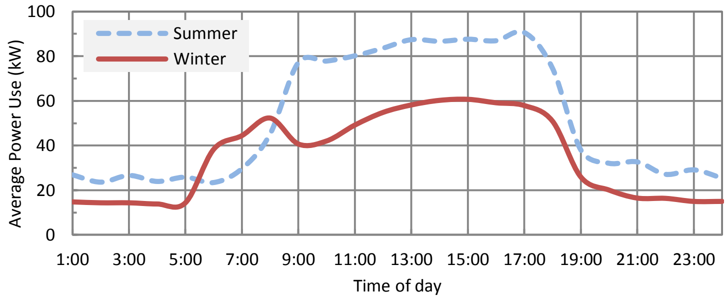

Fig. 7 Enterprise 1 HVAC loads summer and winter average day

Comparing the HVAC summer and winter average loads from the SBRC building (Fig. 6) to those of Enterprise 1 (Fig. 7), it is observed in Fig. 7 that the daily behaviour of the commercial office building is more consistent across the two seasons, although a difference in magnitude is observed with heating loads being lower than cooling loads – the inverse of the behaviour seen in the SBRC building.

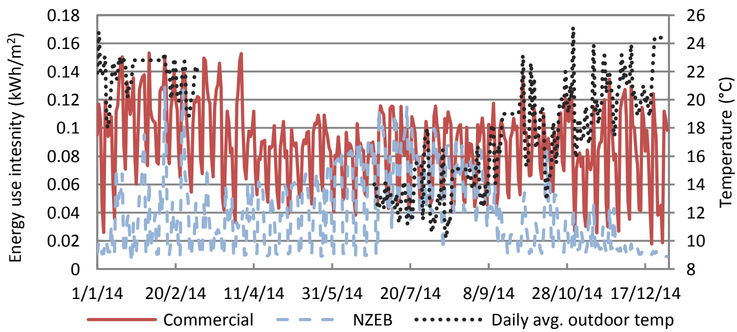

Fig. 8 HVAC energy use intensity comparison - 2014

Comparing the HVAC energy consumption of the two buildings in similar terms, the HVAC energy use intensity is shown in Fig. 9. The daily average outdoor temperature has also been plotted in this figure apart from a section for where data was unavailable. The energy use intensity (EUI) observed during winter (June to August) is very similar between the two buildings. The reasons for this are that the maximum outdoor temperatures in this location are lower than the acceptable indoor comfort limit. This means that the SBRC building – although designed to operate with mixed-mode natural ventilation – must rely more heavily on artificial heating during winter to achieve acceptable thermal comfort standards. The advantages of using natural ventilation at the SBRC become apparent during warmer months, with significant energy savings observed during these periods when compared to the conventional building. The result is that the SBRC building annual HVAC loads are only 45% of the HVAC loads in the conventional building.

The overall energy intensity of the SBRC is compared the energy intensity data for Australian commercial buildings from [10] and the results are presented in Fig. 9.

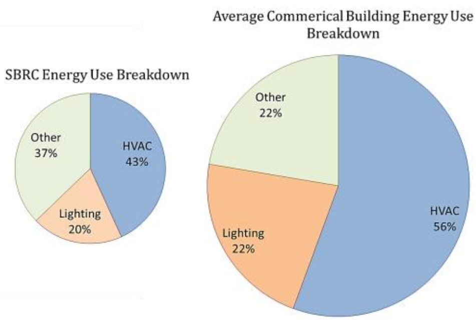

Fig. 9 Energy intensity of case study NZEB compared to typical commercial buildings.

While the magnitude of the SBRC energy intensity is much less than the typical commercial buildings, as per design expectations, it is also noted that key building loads of HVAC and lighting are a significantly less proportion of total load, from 78% in typical commercial buildings to 63%.

5. Conclusions

The results presented here represent NZEB performance in a temperate climate, and would differ significantly for more extreme conditions. The climate in this location aligns well with a reasonable occupant comfort band, allowing natural ventilation to work successfully within the NZEB for all seasons except winter. The reliance of the NZEB on natural lighting means that the lighting power density (LPD) can be 5 times lower than the commercial building. This is also a function of building design and a layout which maximises the natural light entering the building.

Measurements and analysis undertaken illustrate the effectiveness of NZEB concepts for the reduction of energy use. Natural ventilation in mild climate zones can achieve significant savings when implemented in HVAC strategies. Controlling artificial lighting according to available daylight has the potential for significant energy savings, depending on the building design. Low lighting power densities and daylight harvesting can cut lighting energy consumption significantly. However the building envelope and layout must be properly considered to ensure success. Future work in this area aims to quantify the energy savings impact of the various efficiency technologies through detailed modelling of the two buildings.

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