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Editorial

Understanding the design and demonstrating the operational performance of Net/Nearly Zero Energy buildings (NZEB) is critical to further their adoption by clients and practitioners in the building and construction industries. At the outset, economic feasibility remains a critical factor influencing decision making for NZEB practices. And while progress is begin made to collate and analyse energy and carbon performance data to benchmark performance, the success of these buildings in the long term depends to a large extent on occupant or user engagement for optimal performance. International perspectives on these issues are presented in this volume of the journal.

Computer building energy simulations are powerful tools to evaluate the energy and environmental performance of buildings at the design stage. Joe Huang shows that these tools facilitate the assessment of different design and energy strategies and technologies. In quantifying energy saving potential, these simulations provide a useful baseline from which to compare and verify the actual performance of buildings after occupation. These tools have also played a critical role in setting the standards in the development of green building rating systems and building energy policy. In Hong Kong's unique high density and highrise environment, energy simulations require careful consideration of modeling assumptions including local conditions, changes in environmental conditions for different building heights, impact of neighboring buildings on solar radiation, and microclimate effects on temperature and winds.

With much of the building stock comprising of existing buildings, there remains great potential to retrofit the existing building stock to low carbon design. In their paper, Xi Liang, Wei Pan, Mengfei Jiang, Yipu Guo, Jinghong Lyu, Jia Li and Xinyu Chen advocate that it is economically viable to retrofit a commercial building to low carbon design over a lifetime in Edinburgh. Potential rent increases is a significant driver for low carbon retrofits. They recommend the development of standards and policy to support the design of new buildings to be low carbon building retrofit ready. This study provides a basis to examine and further develop the economic case for low carbon retrofits in Hong Kong.

The low operational energy performance benchmarks of recent NZEBs can be seen in the demonstration case study of the China Academy of Building Research Nearly Zero Energy Building. Through the integration of a high performance building envelope, energy conservation building technologies and smart use of renewable energy, Wei Xu, Huai Li, Zhen Yu, Jianlin Wu and Shicong Zhang found that the building's energy consumption is 23kWh/m²/yr from its first 2 years of operations—8% lower than the original annual energy consumption goal of 25kWh/m². This low benchmark is valuable for future research and development in China.

In terms of energy performance benchmarking in the residential building sector, Canada has long been a leader at the forefront as shown in the EcoTerra™ house—an innovative residential nearly zero energy house with an energy consumption of only 13kWh/m². Bruno Lee and Rana Habibi examined research that have been conducted on this innovative near zero energy house. With many years proven operation, the case study shows that in using integrated design, prefabrication and commercially available technologies, NZEB is feasible and similar strategies and technologies can also applied to houses in other locations with a similar climate.

Though often overlooked, building occupants or users play an important role in influencing the management and performance of low energy buildings. In their research, Karishma Kashyap, Usha Iyer-Raniga and Matthew Francis studied the actual versus expected performance of 2 university buildings with 5 star Green Star accredited ratings in Melbourne Australia. Through conducting post occupancy evaluations (POEs), they found that a major source of dissatisfaction with the buildings was the lack of engagement with building users in the design and use of the buildings. The study highlights the importance of user feedbacks in developing strategies for efficient management of buildings to achieve energy performance goals and optimise building performance. Their lessons and insights support the wider use of POEs and user feedbacks as a strategy for building performance management and improvement in the building and construction industries in any context.

The Use of Simulations to Study the Energy Performance of Buildings in Hong Kong

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Over the past 30 years, computer building energy simulations have become a useful and powerful tool to study the energy and environmental performance of buildings. Since most of the construction in Hong Kong are of high-rise buildings, the use of building energy simulations there would frequently be for tall or super-tall buildings in a dense urban environment.

Such kind of building energy simulations has some unique characteristics. In addition to the creation of a large thermal model of the building, the environmental conditions such as the outside temperature, humidity, solar radiation, and wind speed may differ for different parts of the building. Furthermore, since the available weather data are generally from the airport, there may be microclimatic variations due to terrain differences from the airport and the building site, as well as the urban heat island effect.

This paper will give an overview of the use of energy simulations to assist building energy design, evaluate the relative merits of different energy strategies and technologies, and compare simulated results to actual measurements of the building after completion. It will then discuss the special needs for doing energy simulations of tall and very-tall buildings, illustrated by simulations of actual projects.

Keywords: Building energy simulations, computer modeling, tall buildings, Hong Kong

Joe Huang is president of White Box Technologies, a small consultant company specialising in building energy simulations and the development of weather files for use in simulations. Prior to his retirement in 2007, Joe worked for 26 years as a Staff Scientist at Lawrence Berkeley National Laboratory, during which he was involved in the maintenance and use of the DOE-2 energy simulation program starting in 1981, and was a member of EnergyPlus Development Team from 1998 through 2004. He has worked on many projects using simulations to analyse building energy performance and to support building energy policy, such as energy standards and rating systems. Joe has taught building energy simulations or worked on building energy standards in various countries, including Mexico, China, Egypt, and Tunisia. Joe has an undergraduate degree in Physics from Stanford University and a Master's degree in architecture from the University of California in Berkeley

Progress of Building Energy Simulation over the Past 30 Years

The rapid development of Personal Computers (PCs) over the past 30 years has propelled the development of Building Energy Simulations as a tool for understanding how buildings use energy and quantifying the energy-saving potentials of improvements in the thermal integrity of the building shell, the efficiency of the building's Heating, Ventilation, and Air-Conditioning System (HVAC), as well as identifying energy waste in the operations and use of the building.

Table 1 shows the evolution of building energy calculation methods starting with steady-state Degree Day Methods in the 1930's down to simplified and detailed Simulation Methods first developed in the 1980s. The last method shown in Table 1 (Correlations) is not an actual calculation, but using a database of precalculated simulation results to estimate building energy performance.

Method	When	Example	Application
Degree-day	1930s	*CIRA, EEDO*	small residential, heating only
Bin Method	1970s	*ASEAM*	small to intermediate commercial
Simplified Simulation	1980s	*Trane Trace, Energy10*	all building types, energy and simplified demand calculations
Detailed Simulation	1980s	*BLAST, DOE-2, EnergyPlus*	all building types, detailed energy and demand calculations
Correlation	1980s	*PEAR, SLR*	typical designs, approximations

Table 1 Different methods used for estimating building energy use

The first attempts to predict building energy use started in the 1930's when utility companies in the US Midwest found that the demand for coal to heat buildings could be estimated by the number of Heating Degree Days (HDD), which is number of degrees that the average daily temperature falls below a base temperature (65°F or 18.3°C), aggregated over the entire year. The basic concept is that the base temperature represents the balance point temperature for a building, below which the building will require mechanical heating to maintain indoor comfort. When air-conditioning became popular in the 1950's, the same concept was used to define Cooling Degree Days (CDD), although the relationship between CDD and air-conditioning energy use is not as good as HDD to heating energy use, due to the significance of solar heat gain and humidity on air-conditioning loads.

The next advance in building energy calculations is the development of the Bin Method where the weather conditions over a year are separated into categories or bins depending on their temperature, humidity, time of day etc. Typically, a bin would cover a 5°F or 2°C range of temperatures over a month, with a number showing how many hours fall within that bin. The coincident average solar radiation, wind speed, humidity, etc. for the hours within a bin can also be calculated. The weather conditions for each bin are then used to calculate a building's heating or cooling energy use, which are then multiplied by the number of hours for each bin. The energy use for all the bins are then added together to derive the building's total heating and cooling energy use. Although the Bin Method is certainly more detailed than the Degree Day Method, it is still a calculation rather than a simulation, since the method cannot account for dynamic effects such as the thermal response of the building to changing weather conditions.

The Difference Between Energy Calculation and Simulation

Although calculation and simulation are sometimes used interchangeably, they differ in how they derive the building's energy use.

- A *calculation* uses simplified, often steady-state assumptions, to estimate the net effect of heat flows on building energy use over a long period of time.

- A *simulation* attempts to replicate at each time-step (typically an hour, but sometimes even shorter) the fundamental thermal processes affecting a building, as they would occur in reality.

Development of Building Energy Simulation Programs in the United States

The Energy Crisis the US faced in the wake of the Organization of the Petroleum Exporting Countries (OPEC) oil embargo in 1973 brought attention to how energy was being used in the US economy. Since one-third of the total US energy use was consumed in buildings, this gave rise to a need to better understand building energy use, which in turn drove the creation of Building Energy Simulation (BES) programs. Since BES became widely available in the 1980s, they have become indispensible tools for improving building energy design, and for rationally setting the requirements for building energy standards. Practically all modern building energy standards, such as those in the US, Australia, and throughout East Asia including China and Hong Kong have been developed using BES. Furthermore, in many of these countries and economies, demonstrating compliance to building energy standards are also done using BES.

Figure 1 shows a timeline of the evolution of BES programs in the US from its beginning in the early 1970s to the early 2010s (RMI, 2011). It is apparent that all the major BES programs still in use today have taken decades to develop. They can be broadly categorised into three types of BES programs:

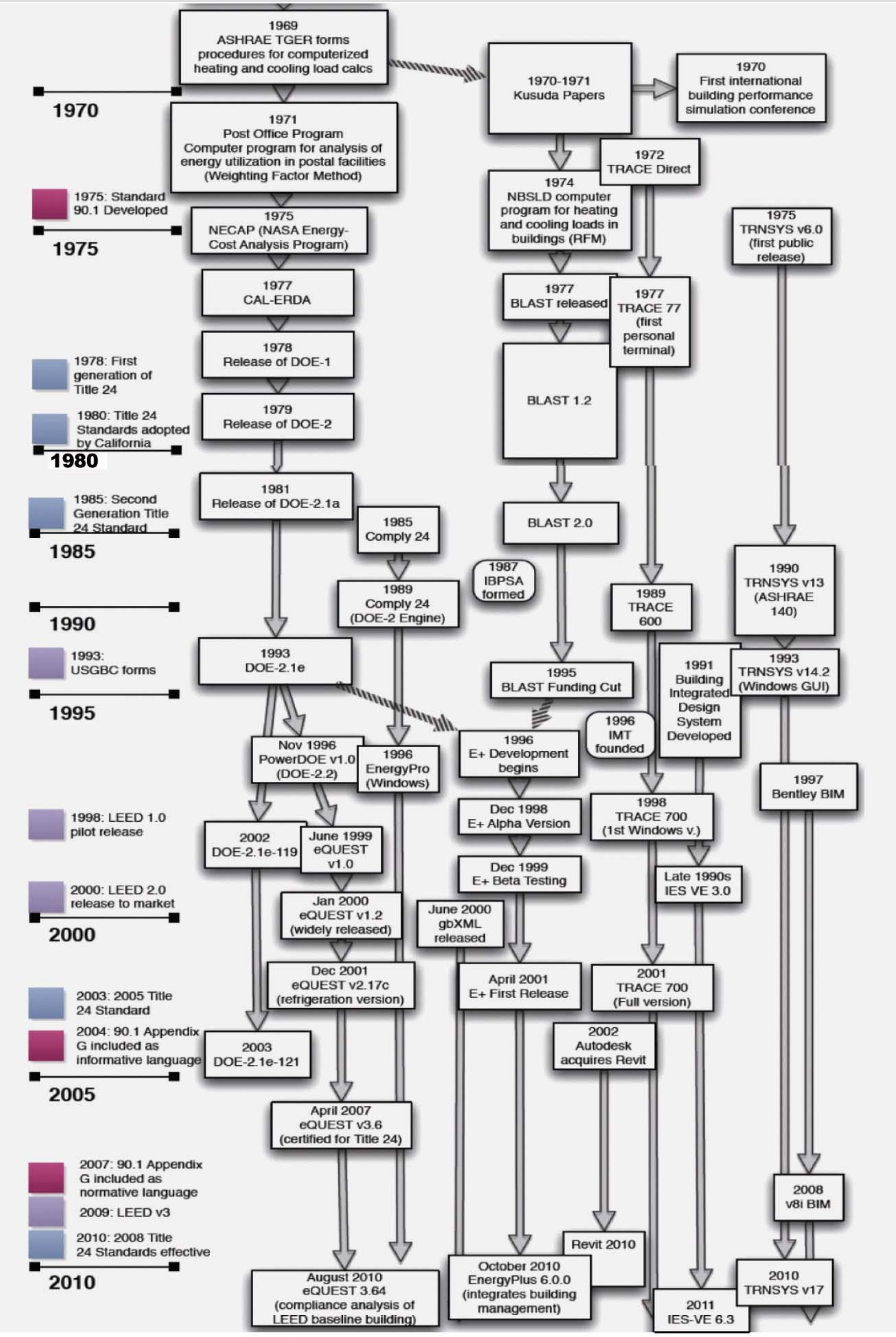

Figure 1 Timeline of building energy simulation programs in the US

1. Public programs originally developed through government funding, i.e., DOE-2, BLAST, and EnergyPlus, although later maintenance, improvements and user interfaces could be developed by either public (Open Studio for EnergyPlus) or commercial entities (eQUEST for DOE-2, DesignBuilder for EnergyPlus).

2. Commercial BES programs, i.e., TRNSYS and IES-VE.

3. Commercial programs originally developed by equipment manufacturers for equipment sizing and selection, but now also adapted to do annual energy simulations, i.e., Trane Trace, HAP, and TAS.

Building Energy Simulation Tools currently being used in the US

According to a survey conducted by the Rocky Mountain Institute in preparation for a two–day Building Energy Modeling Summit held in March 2011, the usage of different BES programs are as shown in Figure 2 (RMI, 2011).

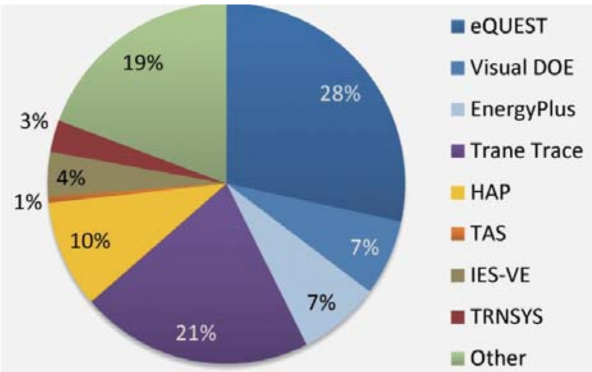

Figure 2 BES programs used in the US in 2011

Comparison of Simulated to Measured Building Energy Use

The accuracy of BES has always been a contentious topic, and critics have pointed at the large dispersion between simulated and measured data to say that simulations are not very reliable (see Figure 3). Although the algorithms in BES can be improved, a major cause for such large differences is that the actual conditions and operations of the buildings were not the same as assumed in the computer models.

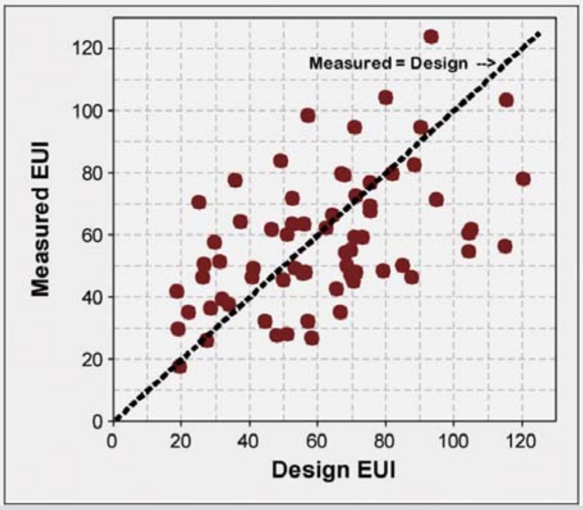

Figure 3 Measured versus design (simulated) EUIs for 121 LEED NC buildings (Turner and Frankel, 2008)

Since the LEED simulations shown in Figure 3 were done before the buildings were built, they relied on standard operating conditions (setpoint temperatures, hours of operation, number of occupants, etc.) following ASHRAE 90.1 guidelines or general engineering assumptions. The fact that despite the large dispersion, the average design EUI compared closely to the measured EUI indicates that modeling rules and the BES results do agree with actual measurements on average.

What has been achieved with Building Energy Simulation over 30 years?

Although BES continue to evolve, and there remain many areas for improvement, there is general agreement among engineers and scientists that simulations provide the most detailed and reliable method available to date for understanding building energy performance.

This is demonstrated by the following developments:

1. HVAC design calculations are now always being done using computer simulations;

2. Simulations have been used increasingly both to set building energy standards levels or to demonstrate compliance;

3. Green building rating systems, e.g. LEED, and utility-sponsored incentive programs rely on simulations to verify superior energy performance; and

4. High-performance and net-zero buildings use simulations either for design or to verify energy performance.

Examples of Actual Projects where Building Energy Simulations were used

The author's work over the past thirty years was largely in building energy research and policy. He had the opportunity to apply BES in the design and evaluation of several projects in China. These are briefly described below, followed by observations of the lessons learned.

US–China Demonstration Energy-Efficient Office Building

This was a joint project between the US Department of Energy (DOE) and China's Ministry of Science and Technology (MOST) to construct a demonstration energy-efficient office building in Beijing (Zimmerman *et al*., 2000).

Figure 4 Artist's drawing of US-China Demonstration Energy-Efficient Office Building

The project started in 1998 and did not end until 2004 with the final completion of the building. MOST was responsible for the actual construction of the building, but Huang worked with the project architect on the building's energy design. The DOE-2.1E program was used to explore design alternatives and identify the most effective energy-saving strategies.

For example, Figure 5 shows a computer sketch of a possible design with two small glazed atria on the southwest and southeast sides of the basic building. The simulations showed that the atria was not beneficial due to increased air-conditioning during the summer and so were abandoned in the final design.

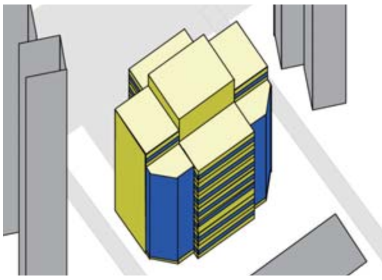

Figure 5 Computer sketch of building energy model done using DOE-2.1E

Table 2 shows the final 12 recommended energy measures based on hundreds of simulations, followed by cost-effectiveness calculations for all the measures (Zimmerman *et al*., 2000).

Figure 6 shows that the same recommended measures would produce a 40% reduction in energy use from the architect's preliminary design, which complied with the 2000 Beijing residential energy standard because the public building energy standard had yet to be developed, and had already incorporated Huang's previous recommendations on the building shape and orientation.

Table 2 Recommended energy-efficient strategies for the US–China Demonstration Energy-Efficient Office Building

1. No change in insulation levels
2. Energy-efficient lighting
3. Selective low-E windows
4. Reduce east and west-facing windows
5. Recess windows for solar control
6. Increase perimeter area for better daylighting
7. Bi-level lighting switches
8. Occupancy sensors
9. Light-colored roofs and walls
10. High-efficiency staged chillers
11. Natural ventilation and night venting
12. Energy Management System (EMS)

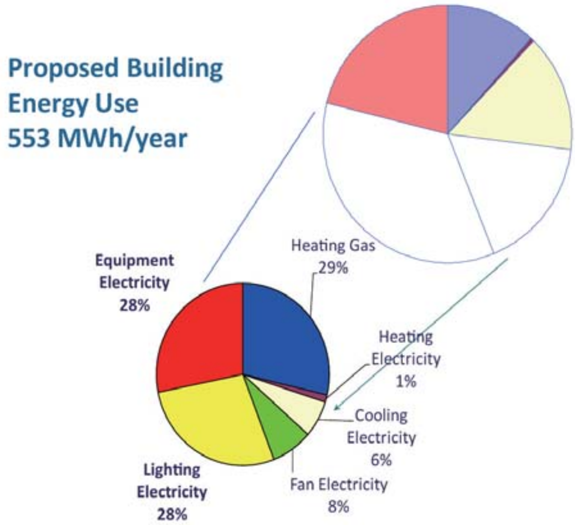

Figure 6 40% energy reduction in US–China Demonstration Energy-Efficient Office Building from architect's preliminary design

[1] China's Design Standard for Energy Efficiency of Public Buildings (GB 50189-2005) was not completed until 2004, when the demonstration building had already been completed. Huang was involved in the development of GB 50189-2005 from 2001-2004.

Beijing Olympic Village "Micro-Energy Building"

This project was another collaboration between US DOE and the Guo'ao Investment Company responsible for the construction of the Olympic Village and several other venues for the 2008 Olympic Games.

The aim of the project was to design and construct a very low energy building in the center of the Olympic Village that would function as an athlete's center during the Games, and be turned into a kindergarten after the Games when the Olympic Village will likewise become a residential development. The chief engineer wanted to make it a landmark low-energy building and coined the term, "micro-energy" (微能耗建筑) because he thought it sounded better in Chinese.

As in the earlier demonstration energy-efficient building, the developer was in charge of the actual design and construction, while Huang used EnergyPlus to analyse the performance of the building and the HVAC system. Although Huang enlisted the help of Bob Kobet, a US architect experienced in designing green schools, the developer selected the design by their in-house A/E firm (Beijing Tianhong Design, 2006).

Figure 7 Artist's drawing of Beijing Olympic Village "Micro-Energy Building"

The developer also worked with a professor at a well-known university who designed a very complex HVAC system that included Variable Refrigerant Flow (VRF) radiant heating and cooling, ground source heat pumps, seasonal thermal storage, desiccant cooling, and solar heating (Shi, 2006).

The curved walls of the building design was a challenge to model, which was accomplished only by using DesignBuilder, a commercial user interface for EnergyPlus that handled non-rectilinear surfaces by decomposing them into multiple triangles. The HVAC system was so unusual and complex that it was impossible to model with EnergyPlus, so it was decided to simulate only the building loads. Figure 9 shows the final building-only model that was developed.

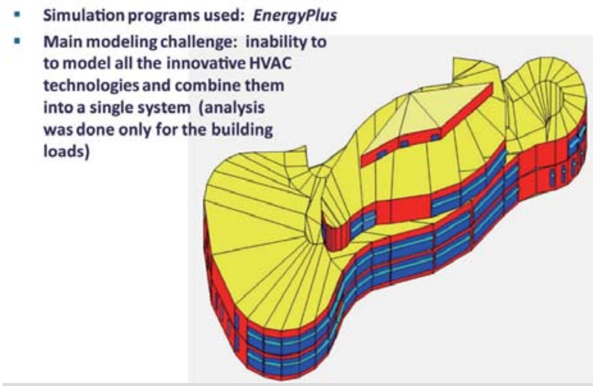

Figure 9 Computer modeling of the Beijing Olympic Village "Micro-Energy Building"

Because the opening date of the Olympic Games could not be delayed, there was tremendous pressure to finish the "Micro-Energy Building" by August 2008, making it impossible to suggest any design changes. The building was completed on time, and the US Treasury Secretary was on hand during the Games to award a LEED Gold Plaque for the Olympic Village (see Figure 10).

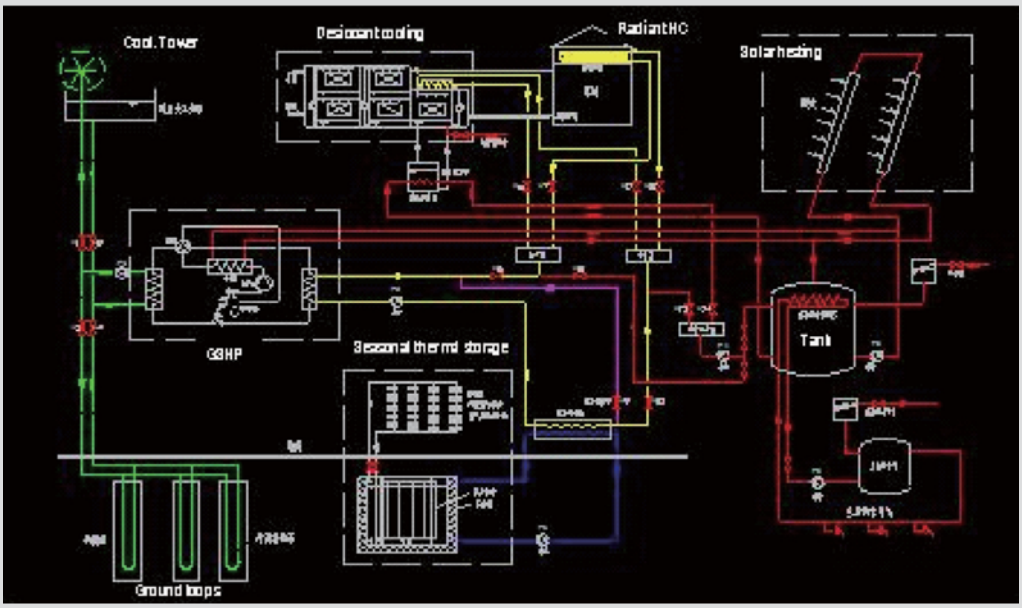

Figure 8 HVAC diagram for the Beijing Olympic Village "Micro-Energy Building"

Figure 10 The "Micro-Energy Building" upon completion at the Olympic Games (August 2008)

After the dust had settled, Huang was able to revisit the "Micro-Energy Building" in 2012, which was now being run as a kindergarten as originally planned. The condition of the building was worse than originally feared. The radiant system was not able to keep the building warm in the winter, so workmen installed standard split systems and knocked holes in the windows for the refrigerant loop. Other innovative technologies such as the seasonal thermal storage system were never operational and simply abandoned (see Figure 11).

Figure 11 Revisiting the "Micro-Energy Building" four years later in Winter 2012 and lessons learned

Some systems did not perform as anticipated; others were never used, and attempts to fix problems compounded them in many ways.

A strong lesson from this project was to avoid using too many unfamiliar technologies, and not get so distracted by computer modeling that the basics of energy design get overlooked (One reason the building was very cold in the wintertime was that the doors did not have weatherstripping).

Special Considerations when Doing Building Energy Simulations in Hong Kong

Researchers and academics in Hong Kong have been among the earliest adopters and users of Building Energy Simulations (BES). For many years, The University of Hong Kong was an International Resource Center for the DOE-2 program not only for Hong Kong, but for the wider East Asia area, including China, Taiwan, and Japan.

Therefore, many of the following considerations or concerns when using BES may be very familiar to users in Hong Kong. The considerations are separated into two broad categories – General Considerations that apply whenever BES is introduced to a new location (see Table 3), and Special Considerations that recognise the unique circumstances in Hong Kong (see Table 4).

Table 3 General considerations when doing building energy simulations in Hong Kong

- Verify that the defaults, material properties, equipment characteristics, occupancy patterns, etc. are appropriate for local conditions
- Gather as much monitored data as possible, and use them to calibrate the computer models
- Model what's actually happening, and not theoretical specifications and code requirements
- Focus on the big picture, and don't get distracted by small technical details
- Calibrate, calibrate, calibrate
- Use the best or most appropriate weather data

Table 4 Special considerations when doing building energy simulations in Hong Kong

- Has one of the highest concentration of tall buildings in the world
- Need to account for solar shading from adjoining buildings
- Dense "forest of buildings" can create urban microclimates that are very different from "rules of thumb" about how conditions change above the ground
- Mesoclimate differences between the airport and downtown can be very large

All of these special considerations are related to getting right the microclimate to which a building in Hong Kong would be responding. Although meteorologists have developed "rules of thumb" for several of these effects, it needs to be pointed out that such rules may not always be reliable or correct.

Lapse Rate Temperature Corrections for Height Above Ground

It is a well-known fact that because of adiabatic cooling, air temperatures will fall at an average rate of 1°C for every 100m of elevation, which is often called the "Lapse Rate". Therefore, the top floor of a 300m tall building will experience air temperatures that are 3°C cooler than at the ground floor. Some BES programs, such as EnergyPlus, will automatically make this Lapse Rate correction to the weather data. However, it should be noted that this is an average Lapse Rate, and that actual conditions may differ substantially depending on the weather conditions and the local surroundings. For example, dense urban areas such as in Hong Kong have a great deal of air mixing, so that the Lapse Rate may be reduced or even nonexistent. Figure 12 shows that Lapse Rates can be quite different depending on the weather conditions, and can even be negative when there is an inversion.

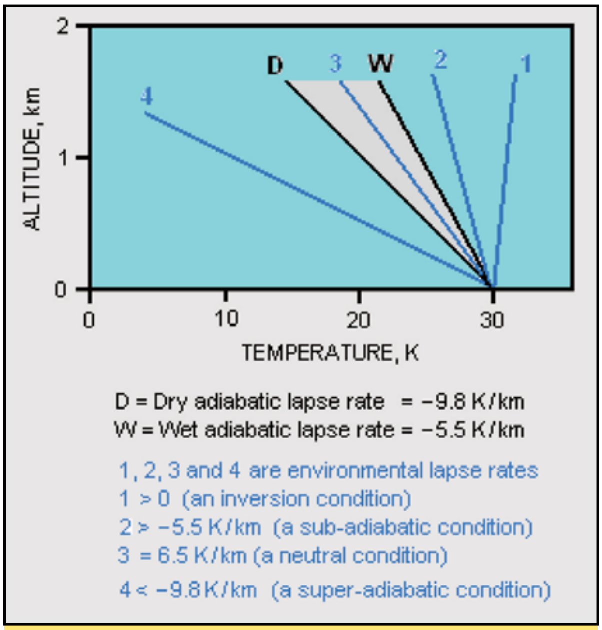

Figure 12 Different lapse rates depending on atmospheric conditions

Wind Speed Variations with Heights Above the Ground

Another well-known "rule of thumb" is that the wind speed will increase logarithmically with the height above the ground (see Figure 13). It should be remembered that these wind speed profiles have been measured in open fields and may not be appropriate for dense urban areas such as in Hong Kong. The main reason that wind speeds increase above the canopy is because there are no more obstructions. Note that in Figure 13, the urban canopy is assumed to have a height of 100m. If in Hong Kong, there is a substantial number of tall buildings in excess of 100m, then the wind speed profile shown on the left of Figure 13 may not be appropriate.

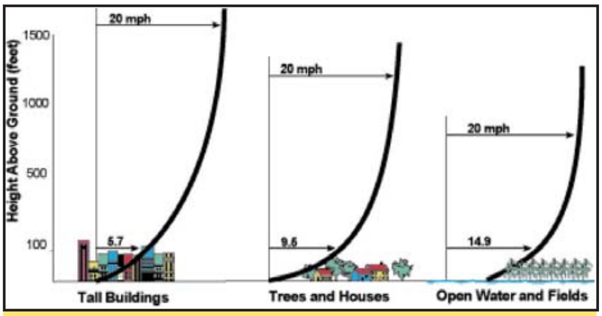

Figure 13 Typical wind speed profiles for height above ground

Microclimatic Differences Between the Airport and Downtown

The available weather data for most cities around the world, including Hong Kong, are taken at the airport. It is well-known that the larger the city, the more intense is the "Urban Heat Island" where temperatures downtown are higher than the surrounding rural area where airports are often located.

The intensity of the Urban Heat Island in Hong Kong needs to be measured and documented. Although Hong Kong has extremely dense urbanised areas, its Urban Heat Island may be ameliorated by the closeness to the surrounding waters, as is also the airport. Furthermore, there have been other studies showing that the Urban Heat Island can cause an urban area to be cooler during the morning, and significantly hotter than the surrounding area only after sunset, when the temperatures in rural areas fall much quicker.

Case Study of Simulations for a Super-tall Building in Chengdu

The final section of this paper describes a simulation study of a super-tall building in Chengdu done by an architect, Craig Burton of PositivEnergy Practice in Chicago, where he accounted for the variations in climatic conditions with height above the ground and showed the effects on the simulation results (Burton, 2015).

Figure 14 is an artist's drawing and Table 5 gives the general specifications of this 435m+ tall mixed-use commercial building to be built in Chengdu, China.

Figure 14 Artist's drawing of Chengdu building

Table 5 General building specifications

- Mixed use very tall building
- Located in Chengdu, China
  HDD (18.3°C) 1,365
  CDD (10°C) 2,715
  (at 10 m above ground level)
- ASHRAE Climate Zone 3A
- Dedicated Outdoor Air System (DOAS) units serving Fan Coil Units (FCUs) and Variable Air Volume (VAV) systems throughout tower
- Simulations done using IES-VE

The expected changes in the dry-bulb and dewpoint temperatures, atmospheric pressure, and relative humidity are adjusted as described below:

Correction for Dry Bulb Temperature

Environmental Lapse Rate formula

$T_{db} = T_b + L*(H_z-H_b)$

$H_z = (E*z)/(E+z)$

T_b	Variable from weather file	K
L	-6.5	K/km
E	6,356	km
z	Variable for Elevation	km
H_b	0	km

Correction for Dewpoint Temperature

August-Roche-Magnus approximation

$Tdp =(243.12*(\ln(RH/100)+(17.62*Tdb)/(243.12+Tdb))/(17.62 - (\ln(RH/100)+(17.62*Tdb)/(243.12+Tdb))))$

RH	Variable adapted from weather file	%
T_{db}	Variable from weather file	C

Correction for Atmospheric Pressure

$P=Pb*(Tb/(Tb+Lb*(h-hb)))^\wedge(go*M)/(R*Lb)$

P_b	Variable from weather file	Pa
T_b	Variable from weather file	K
L_b	-0.0065	K/m
h	Variable for Elevation	m
h_b	0	m
M	0.0289644	kg/mol
R	8.31432	N·m /(mol·K)
g_o	9.80665	m/s^2

Correction for Relative Humidity

Assume same relative water vapor content at all elevations:

$Pw' / Pa' = Pw / Pa$

$Pw = Pws * RH / 100$

$Pws = 611 * 10\tau$, where $\tau = (7.5 * T_{db})/(273.3 + T_{db})$

$Pw' = Pw * Pa' / Pa$

$Pws' = 611 * 10\tau$, where $\tau = (7.5 * T_{db}')/(273.3 + T_{db}')$

$RH' = Pw' / Pws'$

P_w	Partial water vapor pressure	Pa
P_{ws}	Equilibrium water vapor pressure	Pa
P_a	Atmospheric pressure	Pa
T_{db}	Dry bulb temperature from weather file	C
'	indicates values adjusted for elevation	

Figure 15 shows the vertical layout of the building, with offices below 210m, business suites at 210-305m, hotel from 305-435m, and mechanical floors above 435m.

Figure 15 Vertical layout of Chengdu building

The base weather file was an IWEC2 "typical year" weather file for Chengdu Airport. For each of the five building elevations, a modified weather file was created with the corrections as described earlier. As a result, the HDD and CDD changed markedly between the ground floor and the top floor (see Figure 16).

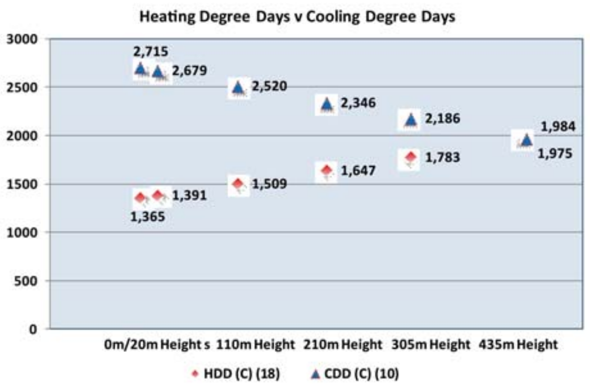

Figure 16 Adjusted weather files

The impact of the modified weather files on the energy use of the heating and cooling coils is shown in Figures 17 and 18.

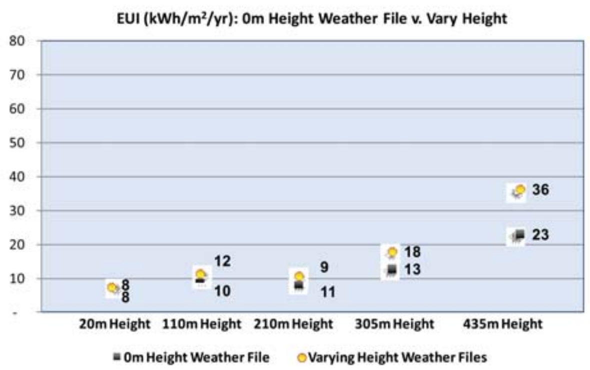

Figure 17 Heating Coil (DOAS) consumption (kWh/m²/yr)

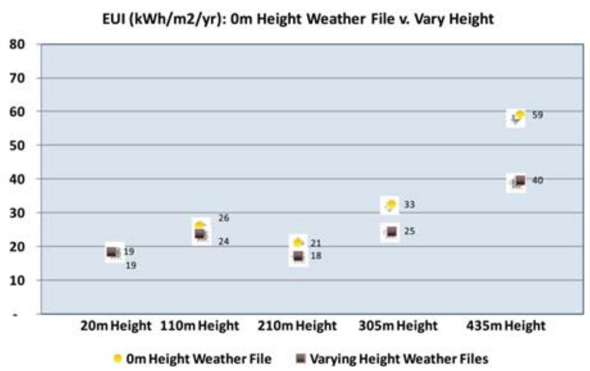

Figure 18 Cooling Coil (DOAS) consumption (kWh/m²/yr)

The net impact on total energy use is not very large, since increased heating is balanced against decreased cooling energy use. However, for sizing the DOAS coils on each individual floor, the differences are dramatic (see Figure 15).

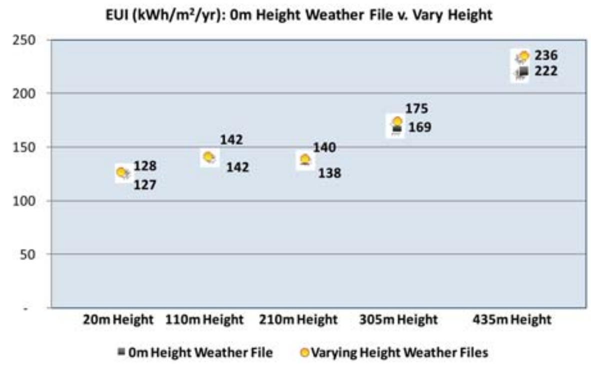

Figure 19 Whole building consumption (kWh/m²/yr)

Table 6 shows the differences in the DOAS heating and cooling energy uses between the base weather file and the modified weather files.

DOAS System	DOAS Heating Coils only	DOAS Cooling Coils only	DOAS Electrical only	Annual Energy Impact (whole building)
435m zone	+53%	-33%	-2%	6.5%
305m zone	+37%	-19%	-1%	3.4%
210m zone	+27%	-13%	-1%	1.2%
110m zone	+13%	-6%	0%	0.3%
20m zone	+2%	-1%	0%	0.1%
Total	31%	-14%	-2%	2.3% (over total building consumption)

Table 6 Annual energy comparison (adjusted vs. unadjusted)

Conclusions

It has been almost forty years since building energy simulations were first developed to obtain a better sense of how and when energy is used in buildings. Since its fledging days in the 1980's, simulations have become indispensible tools for the design and operation of energy-efficient buildings, evaluation of energy options for existing buildings, and establishing effective but realistic building energy standards and energy efficiency targets. Although the scientific basis of building energy simulations is equally applicable anywhere in the world, the validity of building energy simulations is also dependent on many modeling assumptions about the building's construction, operation, and usage, as well as the local environmental conditions faced by the building, all of which can vary from place to place. Since building energy simulations have been developed largely elsewhere, their usage in Hong Kong should include careful evaluation of whether the modeling assumptions are appropriate, and that special local conditions are being considered. Because of the high density of tall buildings and urban congestion, changes in environmental conditions for different building heights, the impact of neighboring buildings on solar radiation including reflections, and microclimate effects on temperature and wind are all areas of concern when doing building energy simulations in Hong Kong.

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Assessing the Value of Commercial Building Low-carbon Retrofit in Edinburgh City in Scotland

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The purpose of the current work is to assess the economics in the retrofit of non-domestic buildings in the UK, and recommend policy mechanisms to bridge the gap. This paper gives an overview of evaluation methodologies, including the technology assessment mechanism, financial cash flow valuation method, and the novel real option approach for assessing the value of new buildings designed in a low carbon retrofit readiness status. Detailed analysis of potential benefits from retrofitting existing commercial buildings in Edinburgh City is carried out. Results show substantial financial value in retrofitting a building over a lifetime through assessing the option value. The economic viability of retrofitting a commercial building to low carbon design in Edinburgh is proven to be very high. Thus, it is proposed that new buildings are designed to a 'Low Carbon Building Retrofit Readiness' status ('LCB Readiness'). It would also be beneficial to develop a standard or best practices for low carbon design in commercial buildings.

Keywords: Low carbon building, low carbon building retrofit readiness (LCB readiness), option value, low carbon retrofit

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Introduction

Energy Consumption in the Building Sector

The rapid growth of the world economy requires substantial demand and consumption of energy, resulting in diminishing energy resources and adverse environmental impacts. During the last two decades, the world's total final energy consumption increased by 48% to 9,321 Mtoe while carbon emissions (CO_2) increased by 56%, reaching 32,190 Mt in 2013. This is an average annual increase of 2.1% and 2.4% respectively (Figure 1). The European Union (EU) countries endeavoured to tackle energy and environment issues after the agreement of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. Although subsequent energy consumption and CO_2 emissions seemed to be under control (Figure 2), final energy consumption and CO_2 emissions in the EU contributed 12% and 10% of the world's total numbers respectively (IEA, 2015).

Final energy consumption is usually dominated by the industry sector, followed by agriculture, commercial and public services, residential and non-specified, and the remaining by the transport sector and non-energy use. However, the building sector in developed countries accounts for 20-40% of total final energy consumption exceeding other major sectors (Perez-Lombard *et al*., 2008). In 2004, energy consumption in the building sector in the EU accounted for 37% of final energy use, higher than industry (28%) and transport (32%). In 2010, it increased to 40% of total energy consumption in the EU (EU Commission, 2010). In the United Kingdom (UK), up to 42% of the energy consumed is spent in heating and cooling buildings (DECC, 2015), and 43% of carbon emissions is attributed to the building sector (DCLG, 2015). This is slightly above the European figure and partly due to the shift away from heavy industry towards service sector activities (Perez-Lombard *et al*., 2008).

Furthermore, the building sector is expanding. The energy used by domestic and non-domestic buildings accounts for approximately 25% and 18% of UK's carbon emissions (DECC, 2015). It is expected that non-domestic floor area in the UK will increase by 35% by 2050 while 60% of existing buildings will still be in use (LCICG, 2012). Public sector buildings in Scotland emitted 1.2 $MtCO_2e$, which represented 2.3% of Scotland's greenhouse gas (GHG) emissions in 2013. Buildings and other developments can also be environmentally hazardous through poor waste management or inefficient use of resources (DCLG, 2015). Therefore, reducing energy use and GHG emissions in the building sector are essential for tackling climate change. Retrofitting existing buildings is a significant opportunity to help improve energy efficiency and reduce GHG emissions in the UK.

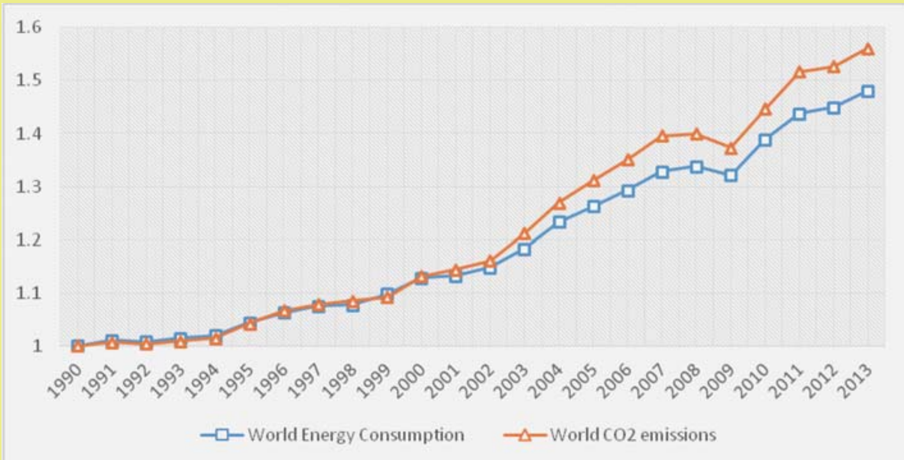

Figure 1 World's total final energy consumption and CO_2 emissions since 1990 (Source: IEA, 2015)

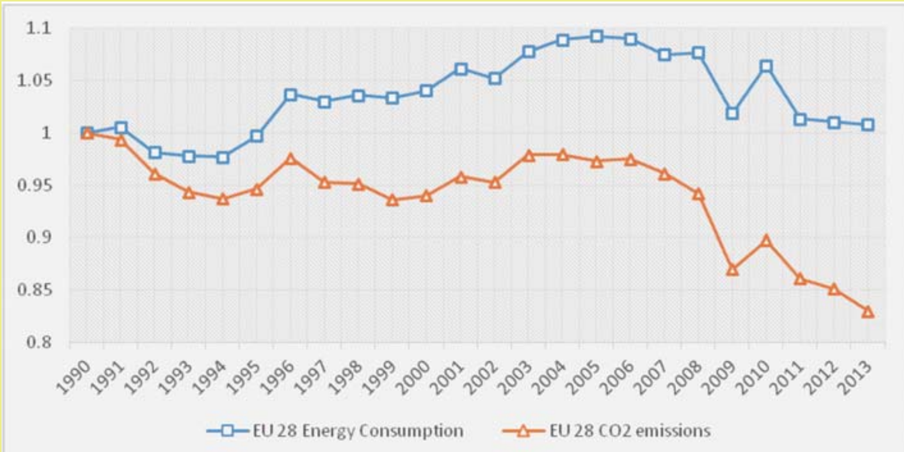

Figure 2 EU 28 countries' total final energy consumption and CO_2 emissions since 1990 (Source: IEA, 2015)

Building Energy Policy in Scotland

The Scottish Government has declared a strong commitment to lower net carbon emissions by 80% by 2050 compared to the 1990 baseline. The interim target set for year 2020 is to lower net emissions by at least 42% to the baseline. Moreover, for the period 2011-2019, the annual carbon emission target must be set at an amount that is consistent with achieving the interim and 2050 targets. For each year in the period 2020-2050, the target must be set at an amount that is at least 3% less than the target for the preceding year (The Scottish Parliament, 2009).

The bill for the Building (Scotland) Act was passed by parliament on 20 February 2003, including provisions with respect to buildings, building standards, verification and certification, building warrants etc. In 2007, the Sullivan Report proposed a route map for the delivery of very low carbon buildings, setting aspirations for carbon abatement and energy efficiency in building standards. The report suggested that all owners of non-domestic buildings should conduct a carbon and energy assessment and produce a programme for building upgrade. The Sullivan Report (2007) also considered ways in which the carbon and energy performance of existing buildings can be improved. The introduction of legislation to require all owners of non-domestic buildings to conduct carbon and energy assessments and produce a programme for upgrading was recommended. Such assessment is listed as section 50 "Non-domestic buildings: assessment of energy performance and emissions" in the Climate Change (Scotland) Bill.

The energy performance of non-domestic buildings, and promotion of energy efficiency and renewable heat were therefore emphasised in the 2009 Climate Change (Scotland) Act (The Scottish Government, 2009). In the same year, the Scottish Government issued the Renewable Energy Framework to support the EU target of utilising 20% renewable energy by 2020, and to play a role in meeting UK's proposed 15% renewable energy target with an aim to go further to 20%.

Almost all of the recommendations from the original Sullivan Report (2007) have now been taken forward. The recent Sullivan Report (2013): A Low Carbon Building Standards Strategy for Scotland revisits previous recommendations to identify ways to further drive the successful implementation of low carbon building standards. A review of energy standards was recommended to align with the EU's Directive for 'nearly zero energy' new buildings from 2019.

The Scottish Government is also using building standards and the planning system to help achieve low carbon buildings. The Building Standards Division (BSD) has published new guidelines regarding compliance with building standards from 1 October 2015, including new technical handbooks, with major revisions to Section 6 (Energy) Domestic and Non-domestic. The standard now applies to extensions to non-domestic buildings that increase the total area by more than $100m^2$ or 25%. Figure 3 shows a timeline of the development of building energy policy in Scotland over a 12 year period.

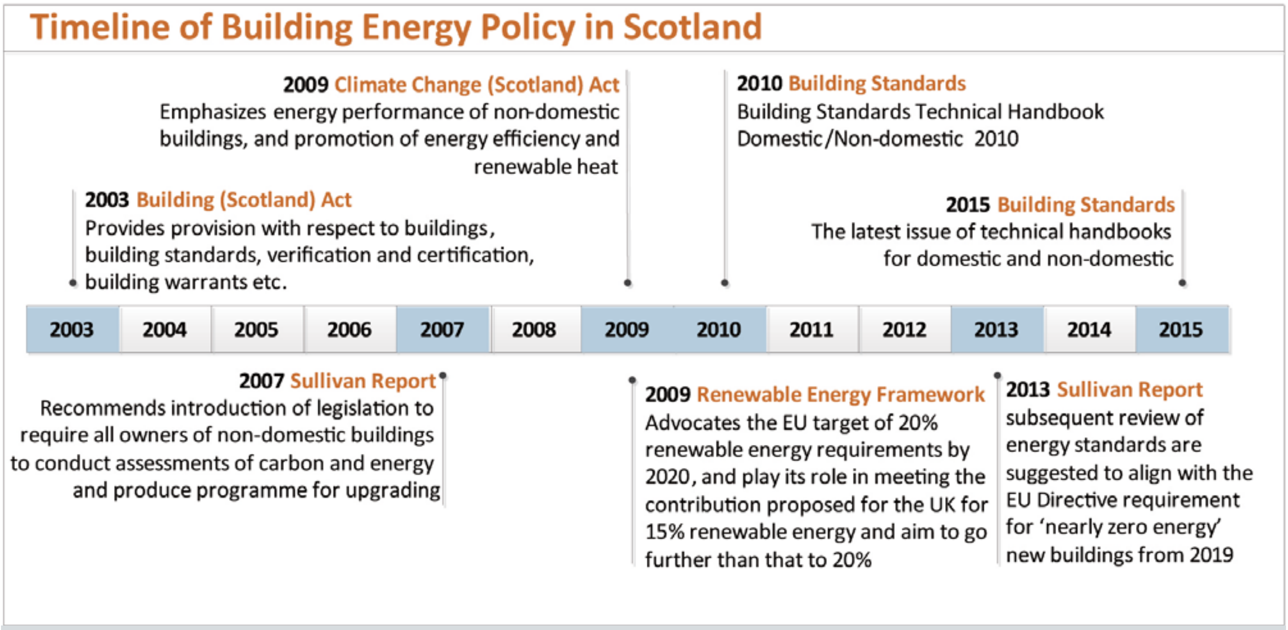

Figure 3 Timeline of building energy policy in Scotland

The Retrofit of Non-domestic Buildings

The main purpose of retrofitting is to extend the beneficial use of an existing building by taking a cost-effective alternative to redevelopment (Markus, 1979). Retrofitting may be driven by property damage, depreciation and the loss of a property's investment value (Aikivouri, 1996). However, since conventional economic performance analysis has been extended with greater consideration of the social and environmental impacts of a business, Mansfield (2009) suggested that sustainability policies with respect to corporate social responsibility (CSR) and socially responsible investment (SRI) may lead to retrofitting to address energy efficiency, CO_2 emissions and other sustainability issues.

Ma *et al*. (2012) identified five steps in the process for building retrofit: project set up and pre-retrofit survey; energy audit and performance assessment; identification of retrofit options; implementation and commissioning; and validation and verification of energy savings. A successful retrofit programme depends on many factors including policy and regulations, retrofit technologies, building specific information and other uncertainties. As there is a wide range of retrofit technologies readily available, reliable estimation of the most cost-effective retrofit options for existing buildings is essential for sustainable building retrofit. The performance of different options is commonly evaluated using energy simulation and modelling.

Economic feasibility analysis that facilitates the comparison of retrofit alternatives can provide an indication of which alternatives are cost-effective, and the trade-offs between capital investment and benefits (Ma *et al*., 2012). Blackhurst *et al*. (2011) examined the costs and benefits of existing local residential and commercial building retrofits aiming to reduce GHG emissions by conducting two case studies: (1) Pittsburgh, Pennsylvania; and (2) Austin, Texas. They analysed the capital and labour costs, as well as net benefits of consumer savings from retrofits and evaluated the trade-offs between capital constraints, social savings, and reductions in GHG emissions. Net present value (NPV) was used to measure net savings. Their results suggested that uncertainty in local stocks, demand, and efficiency significantly impact anticipated outcomes.

Rysanek and Choudhary (2013) augmented the above study by employing a combined engineering–economic assessment model of a building energy system. They modified the standard approach to building energy modelling by using TRNSYS[1] to improve the speed at which accurate performance estimations of numerous retrofit options are made. Meanwhile, Bull *et al*. (2014) assessed energy efficient retrofit options for schools in the UK by conducting dynamic energy simulations of a range of energy retrofit measures using EnergyPlus v.7.2[2] and jEPlus v. 1.4. They introduced life cycle effects on costs and carbon emissions since these retrofits will last for many years. They found that carbon payback is shorter than financial payback and all options and combinations of options repaid the carbon invested in them.

One of the case studies in McArthur and Jofeh's research (2015) involved a large global tenant with 40 properties in their UK portfolio. The tenant's retrofitting goal is to reduce their portfolio's carbon emissions by 50% between 2007 and 2017. To achieve this goal, McArthur and Jofeh identified the best opportunities in the portfolio by assessing and sorting portfolios using historic energy use data. Aste *et al*. (2016) also presented economic analysis referring to local energy efficiency programs for retrofitting existing buildings and for promoting new low emission buildings.

Whilst energy saving and emission reduction might have been 'top priority' in the previous decade, the global economic recession and the public debt crisis made 'energy efficiency cost saving' a popular rationale for retrofitting existing buildings (Rysanek and Choudhary, 2013). Different types of buildings exhibit unique architectural, geographical and operational characteristics, therefore retrofit options must be rationally analysed for every individual building in the building stock. Computational building energy models must be employed to investigate the costs and benefits of these options.

Meanwhile, progress in retrofitting the UK's commercial properties continue to be slow and fragmented. New research from the UK and US suggests that radical changes are needed to drive large-scale retrofitting and that new and innovative models of financing can create new opportunities (Dixon, 2014). Moreover, despite a number of studies on carbon reduction in residential buildings and new buildings, there is limited research into the disaggregated potential for energy and carbon by retrofitting existing non-domestic buildings with more efficient and low carbon designs. In addition, most studies on energy and environmental performance of the retrofit of existing commercial office buildings were carried out based on numerical simulations, more studies with practical case studies on non-domestic building retrofits are essentially needed.

[1] Transient System Simulation Program, used in renewable energy engineering and building simulation for solar design

[2] Updated version in 2012 of EnergyPlus simulation software for modeling heating, cooling, lighting, ventilating, and other building energy flows

Methodology

Since the 1970s, the traditional financial option pricing methodology—the Real Option Approach (ROA), has been applied to value real assets which are either uncertain or flexible (Myers, 1977). This is because an alternative, deterministic net present value method fails to capture the option value involved in sequential decision-making at each decision node[3]. This study applied ROA to investigate the economics of retrofitting a building to low carbon building status.

Existing ROA studies in the energy sector could be classified into three clusters: (1) analysis of private investment decisions under market uncertainty, e.g. electricity, fossil fuel, and/or carbon markets (Rothwell, 2006; Fortin *et al*., 2008; Szolgayova *et al*., 2008; Yang *et al*., 2008); (2) optimisation of Research and Development, commercialisation and diffusion of energy technologies of a firm (Kumbaroglu *et al*., 2005; Tan *et al*., 2007; Siddiqui *et al*., 2007); (3) investigation of public energy policy decision-making in an uncertain or flexible energy system (Lee and Shih, 2005; Marreco and Carpio, 2006; Lin *et al*., 2007; Fuss and Szolgayova, 2010; Zhu and Fan, 2011).

The methodology of this study was built on the knowledge and understanding gained from the existing ROA studies described above. We took the perspective of a project investor (e.g. commercial building investor) investigating the value of a retrofit option in a commercial building. Uncertainty is the driver of the option value. A number of uncertainties may potentially affect this investment decision, including the technology progress ratio (or learning rate), global installed capacity of low carbon building, gas and electricity prices, and carbon price. High learning rate would drive down economy of scales, which helps to increase the attractiveness of the retrofitting option. The global installed capacity should be examined to identify constraints of low carbon building worldwide. Gas and electricity prices, and the carbon price, are positively correlated to building retrofitting.

There are significant uncertainties relating to policy in modelling the carbon price and other than existing carbon markets, regulations are in reality likely to be a possible driver for low carbon building retrofit. In this study, we simplified the assumption and assumed the investment was driven solely by market factors.

[3] As a part of a real option model, the investment decision is made at each decision node

To identify the probability of retrofitting a low-carbon building, a stochastic free cash flow model was built, to estimate each year's net present value of future cash flows generated by low carbon retrofit. The net present value of the future cash flow at year T is given by:

$$PV_T(S_t, I_t, O_t, F_t) = \sum_{n=T}^{L} \frac{(S_t - I_t - O_t - F_t)}{(1+q)^t}$$

t	year	Present life of the commercial building at a decision node
L	year	Lifetime of building
PV_T	$	Present value of the future cash flow at year T
S_t	$	Revenue from rental at year t
I_t	$	Investing cash flow at year t
O_t	$	Non-fuel and non-carbon operating cash flow at year t
F_t	$	Payment for electricity, gas and carbon at year t
q	%	Private Discount Rate (required internal rate of return)

The main driver for retrofitting a building into a low carbon building was assumed to be an increase in revenue driven by increased rent and a reduction in the carbon and energy bill. The value of a future retrofit is inherently uncertain and a robust exploration with probabilistic Monte-Carlo analysis was conducted to take this into consideration.

In theory, increasing the number of time-steps would result in higher option values, but actual investment decisions are more likely to be made on an annual basis, because the process to evaluate an upgrade investment decision would incur sunk costs (e.g. detailed engineering and economic assessment, special board assemblies). Therefore, this study was conducted with discrete time intervals to approximate the real decision-making process (Plantinga, 1998). It was assumed that the decision is only made at the end of each year. In other words, if one retrofit takes place in year t, a further upgrade could also be made at year t + N. For a 50 year economic life, there would be 24 time-steps, or decision nodes.

At each decision node, the decision to retrofit a commercial building depends upon the balance between the cost of a one-off capital investment to retrofit and the sum of future cost savings and revenue increase.

Technology learning rates, assumed to be translated into a reduction in the retrofit cost with new low carbon technologies entering the market, were therefore critical to determine the value of the option considered for retrofitting in this study. These learning rates focus on the total capital cost of retrofitting the building. The retrofit cost (RCOST) was modelled by a one-factor learning curve model (Alberth, 2008; Junginger *et al*., 2010), given by:

$$RCOST_n = RCOST_0(\frac{Cap_n}{Cap_0})^{\log(1-m)}$$

$RCOST_n$	GBP	Retrofit cost at year n
Cap_n	m^2	Global capacity of low carbon commercial building at year n
m	-	Learning rate

For simplicity, it was assumed that the technology learning rate and the global deployment capacity rate are not affected by other assumptions or the model specification, so they are exogenous, independent values. There is a lack of study estimating the learning rate for low carbon retrofit. This study assumed a learning rate of 5%. In addition, it was assumed that a stochastic process applies to the technology learning rate (m) and the rate of global installed generation capacity with low carbon retrofit. This follows findings from McDonald and Schrattenholzer (2001) which showed that historical energy technology learning rates are not constant and varies stochastically. However, there is a lack of literature to justify the stochastic process of learning rates and deployment rates for low carbon building. Based on our best knowledge, with reference to past learning and deployment process, the hypothetical learning rate was assumed to follow a mean reverting process and tends to drift towards its long term mean assumption at a hypothetical reversion rate of 0.5. Similarly, the hypothetical deployment rate of installed capacity varies stochastically and drifts towards its mean value with a mean hypothetical reversion rate of 0.25.

The hypothetical technology learning rate and the deployment rate of low carbon building capacity can be written as:

$$Q_t = Q_{t-1} + \omega_m(Q_L - Q_{t-1}) + Z_m$$

ω_m	-	Mean reverting rate
Q_t	$	Rate at year t
Q_L	$	Long run equilibrium Rate
Z	-	Random variable following a standard Wiener process

Thus the main barrier to retrofit is the cost of the upfront capital investment necessary to make a low carbon building. To represent the uncertainty of the price of electricity, gas and carbon, a stochastic process was modelled by a mean reverting process, as in Equation below:

$$P_t = P_{t-1}(1+ \alpha) + \omega_g(P_L - P_{t-1}) + Z_g$$

α	-	Drift factor (growth)
ω_m	-	Mean reverting rate
P_t	$	Price at year t
P_L	$	Long run equilibrium price
Z_g	-	Random variable following a standard Wiener process

To complement the uncertainties in model assumptions for this study, a sensitivity analysis was conducted to investigate the value of retrofit options for different electricity, gas and carbon price growth scenarios, as well as different learning rates and required capital for upgrade. The boundary for exercising the option to retrofit a building was to estimate the probability of exercising the option at each decision node. Thus the ROA decision-making framework is a complex model with the following characteristics:

- It is an American style claim option, i.e. options could be exercised anytime from now to any expiry date;
- Because of the sunk cost in exercising the option, only one decision node per year is considered;
- In the baseline scenario, it is assumed that both the price of electricity and the price of gas are not growing, thus in that case, the drift (i.e. growth) of electricity and gas prices is low; and
- A backward looking algorithm is used to estimate the optimal exercise boundary.

In evaluating a retrofit option (i.e. the net benefit of retrofit), a heuristic approach with four steps was applied to evaluate options to upgrade a building:

(a) Identify the sample paths for each variable undergoing a stochastic process;

(b) Use a least square regression method with Monte-Carlo simulation to estimate the probability of upgrade, and the value of the retrofit option at each option decision node, based on the current retrofit cost and the current information of stochastic variables (i.e. retrofit cost, fuel price, electricity price, carbon, deployment rate, and learning rate);

(c) Estimate the initial value of the retrofit option exercised through a backward deduction approach;

(d) Calculate the mean value of the retrofit options at year 0.

The estimated building rental level at the beginning of period t is x_t. It is clear that x_t depends on the realisations of the rental level in the previous periods, i.e. $x_t \in$. Suppose that the current rental level for low carbon building at market I denotes e_t. I, if a retrofit decision is made, then the rental level (x_t) becomes the current low carbon building market rental level e_t, and the beginning low carbon building market rental level of the next period is e_t, i.e. $x_{t+1} = e_t$. If no retrofit decision is made, then the market rental level remains at x_t and $x_{t+1} = x_t$. The value of retrofit options can be evaluated by the following Bellman equation below.

$$V_t(x_t, e_t, Q_t, P_t) = max\begin{Bmatrix} \frac{1}{1+r} b_{t+1}(e_t, Q_t, P_t) - k_t + \frac{1}{1+r} E[V_{t+1}(e_t, e_{t+1}Q_t, P_t)], \\ \frac{1}{1+r} E[V_{t+1}(x_t, e_{t+1}, Q_{t+1}, P_{t+1})] \end{Bmatrix}$$

where the expectation is taken with respect to the market retrofit cost level of the next period and the terminal value $V_T(x_T, e_T) = 0$.

t	year	Present economic life of the building at a decision node
T	years	Lifetime of the building
V_t	$	Stochastic value of the retrofit option(s) at year t
$E[V_{t+1}]$	$	Estimated value of the retrofit option at year t+1
b_{t+1}	$	Estimated marginal benefit in the present value of operating cashflow at year t+1 with a retrofit option exercised at year t
x_t	$	Building rental level at year t
e_t	$	Estimated market rental level for low carbon building at year t (estimated)
r	%	Risk-free real discount rate
k_t	$	One-off capital cost investment to retrofit the building at year t

The decision to make an additional investment at year 0 to future-proof low carbon readiness depends on the present value of the additional investment required (S_0), and the mean value of the option to be able to retrofit the building. In other words, an additional investment to future-proof a building with low carbon readiness status would be justified if the present value of the investment (I_0) is lower than the anticipated value of the option:

Invest, if $V_0 \geq S_0$ Do Not Invest, if $V_0 < S_0$

S_0	$	Additional investment at year 0 to future-proof the commercial building
V_0	$	Value of the option to be able to retrofit the building to a low carbon status

It should be noted that the investment required to future-proof the building (I_0) is site specific, and would in practice, require a detailed design study. The scope of this analysis was limited to introducing the application of a methodology to an illustrative case study, which could also be used to assist decision-making in real projects. Also, the initial investment I_0 was not added directly to the cash flow model. The outcome of the model was the value V_0 (in $) of the option of being able to retrofit the building under different assumptions for gas price, electricity selling price, carbon price, technology learning rate, and deployment rate. The decision to invest or not in a commercial building is out of the scope of this study.

Case Study - Edinburgh Centre for Carbon Innovation

This study examines Edinburgh Centre for Carbon Innovation—a commercial building in Edinburgh City, Scotland.

Figure 4 Edinburgh Centre for Carbon Innovation (Source: edinburgharchitecture)

Background

The Edinburgh Centre for Carbon Innovation (ECCI) is a hub for the knowledge, innovation and skills required to create a low carbon economy. Hosted by the University of Edinburgh, in partnership with Heriot-Watt University and Edinburgh Napier University, the ECCI supports the implementation of government policies, enhances business enterprise and innovation, and delivers professional training.

Work began on the construction of ECCI's new premises in February 2012. This case study covers the refurbishment and remodelling of space in the University of Edinburgh's Old High School in High School Yards to create an innovation suite, lecture theatres, seminar rooms, exhibition and social spaces.

The building refurbishment complied with the University of Edinburgh Estates and Building Sustainability Strategy. The strategy demonstrates a commitment to social responsibility and sustainability and requires meeting environmental standards which exceed legal requirements. The objective was to create a low energy and highly efficient building which would achieve the minimum BREEAM rating of 'Excellent', with an aspiration to be the first listed or refurbished building to be awarded 'Outstanding'.

Building Description, Design and Construction

Fabric

The ECCI refurbishment project involved a major alteration and extension of the Grade B listed Old High School, where a pair of historic 18th century buildings had been lost. At the rear of the ECCI building, a new café building has been created with meeting and office spaces above. A generous opening within the lecture and teaching space creates a new connection to the adjacent courtyard.

The main structure, inserted within the atrium and all areas of new construction, is a Cross Laminated Timber frame (CLT), with a CLT floor panel system. CLT is said to hold around 4-5 times more carbon than it takes to produce the material. The Structural Engineer assessed the structural steel beams removed from the existing building and many were reused as supports in the construction.

The existing Cullaloe and Blaxter stonework has been carefully repaired and conserved. The 'base' course to the new construction is also Cullaloe stone from Fife. Locally sourced stone is durable and repairable. The upper levels of the new construction are covered in bronze cladding (80% copper and 20% tin). This is a lightweight, durable and recyclable material which reduces the load on the structure. The existing sash windows have been retained and repaired with additional draft proofing and installation of slim line double glazed units in some areas. Deep composite timber studs support the external wall construction. The internal partitions are also timber stud.

Insulation is a combination of flexible wood fibre batts and rigid fibreboard with an airtight internal layer. The wall construction is open to vapour transfer, allowing moisture to move from inside the building, and from within the wall construction to the outside. This improves the internal environment and the health of the construction.

Timber is used for internal floors, ceilings and wall linings. Other floors use linoleum (from natural sources) and carpets. Paint finishes are water based and have high breathability to work in conjunction with the vapour transfer through the external wall construction.

Ventilation

The ventilation strategy is primarily passive natural ventilation. An air source heat exchanger also supplies limited chilled beam cooling to some rooms. Cooling and displacement air are only applied in high occupancy rooms (e.g. lecture theatres).

Lighting

Internal and external lighting is low energy (including LEDs) throughout, with zoned control, and use of sensors to limit usage. Daylight studies were carried out at design stage to maximise the use of natural light and reduce areas of summer overheating.

Water

All sanitary appliances are low water usage. Rainwater harvesting was to be installed, until 14th Century archaeological remains were discovered on site, inhibiting the placement of storage tanks. Permeable landscaping and more soft landscaping are used to control and divert surface water.

CHP

A district Cooling Heating Power (CHP) system was installed to provide heating and power. Photovoltaic panels (covering 30m²) were also installed on the south facing roof surfaces of the rear building.

Modelling Results and Financing Mechanisms

Key Assumptions

As illustrated in the last section, the design of low carbon buildings is site specific. According to research from Qiu (2007), the energy consumption in these buildings range from 70-300kWh/m² per annum. The study developed a generic model for assessing the economic value of the low carbon retrofit option by using data from ECCI. Basic assumptions (e.g. building life, rental cost, discount factor and additional costs) and data calculated from ECCI reports are shown in Table 1 and Table 2. The total cost was GBP6.1M for a contract duration of 20 months and a total area of 4790m². The economic life assumption was 50 years. The baseline gas consumption was 127.4kWh thermal/m²/year and the baseline electricity consumption was 56kWh/m²/year[4]. The baseline carbon emission was calculated as 0.05tCO_2/year using conversion factors given by the Department for Environment, Food and Rural Affairs (DEFRA)[5]. The carbon emission was reduced to 0.04tCO_2/year after retrofitting. The baseline local rental cost in Edinburgh was GBP100/m² in 2016. The retrofit cost was calculated from the information above as GBP764/m² annually.

[4] Calculation based on Edinburgh Centre on Climate Change Stage C. Summary available at http://www.docs.csg.ed.ac.uk/EstatesBuildings/Development/ECCCFurtherInfoDoc4.pdf

[5] Carbon emission conversion factors for gas and electricity are 0.18445 Kg CO_2e/kWh and 0.46219 Kg CO_2e/kWh respectively. More details available at http://www.ukconversionfactorscarbonsmart.co.uk/

Table 1 Static assumptions for economic assessment

Static Assumptions	Unit	Value
Building Life	Years	50
Baseline Gas Consumption	kWh/m² per year	127.4
LCB Gas Consumption	kWh/m² per year	98
Baseline Electricity Consumption	kWh/m² per year	56
LCB Electricity Consumption	kWh/m² per year	43
Baseline Carbon Emissions	tCO_2/m² per year	0.05
Baseline Rental Cost	GBP/m² per year	100
Baseline Retrofit Cost	GBP/m²	764
Discount Factor		6%
Additional Building O&M Cost (Retrofit)	GBP/m² per year	0

The low carbon retrofit cost was GBP764/m² in 2016 with an assumed learning rate of 20%, i.e. assuming a 20% cost reduction per doubling of global capacity in low carbon building. The initial global low carbon building capacity was assumed as 1.2 million m². The initial market rent (GBP100/m²/year) was assumed to grow at 3% with a mean reverting rate of 20% and a standard deviation of 5%. The rental cost was calculated using 80% occupancy rate of six different types of rooms and facilities in ECCI. Thus rental revenue was calculated as GBP145/m²/year[6]. Assumptions of gas, electricity and carbon prices were based on the local market environment.

Table 2 Stochastic assumptions for economic assessment

Stochastic Assumptions	Unit	Base Value	Learning Rate	Drift	Mean Reverting Rate	Standard Deviation
LCB Retrofit Cost	GBP m²	764	20%			
Global LCB Capacity	m²	1200000		3%	5%	3%
Market Rent	GBP/m² per year	100		3%	20%	5%
LCB Market Rent	GBP/m² per year	145		5%	20%	5%
Gas Price	GBP/MWh	20		1%	50%	10%
Electricity Price	GBP/MWh	60		1%	50%	10%
Carbon Price	GBP/tCO_2	10		5%	20%	20%

Results

The estimated option value of low carbon retrofit (Figure 4) is GBP413.8/m². In other words, if a new building is designed for low carbon retrofit, the economic value could increase by GBP413.8/m². The estimated present value of option payoff ranges from negative GBP103.5 to positive GBP944.7. Low carbon building retrofit will provide a payoff greater than GBP500 for approximately 75% of the time.

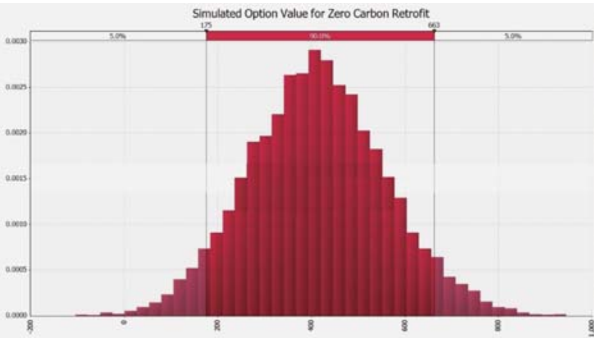

Figure 4 Simulated option value for low carbon retrofit (10000 trials)

Scenario Analysis

The study tested a number of scenarios. If there is no rent increase benefit (i.e. only driven by carbon and fuel cost savings), the option value is dramatically reduced to GBP19.9/m² (Table 3). If there is no fuel saving benefit, the option value is reduced to GBP378.92/m². The initial cost assumption for retrofit influences the option value. When the initial retrofit capital cost is increased to GBP 1000/m², the option value is reduced to GBP177.44/m². If the initial retrofitting cost increase is GBP1100/m², the option value is further decreased to GBP77.78/m².

Table 3 Option values of scenario analysis (10,000 trials) (m²)

No Rent Increase after LCB Retrofit	GBP19.9
No Fuel, Electricity and Carbon Saving Benefit	GBP378.92
Increase from GBP764 to GBP1000/m² initial retrofit cost	GBP177.44
Increase from GBP764 to GBP1100/m² initial retrofit cost	GBP77.78

[6] Calculation based on room and facility rates at http://edinburghcentre.org/Facilities.html

Key Implications

From the generic analyses, the preliminary implications for future studies and policy makers are:

- There is substantial financial value in retrofitting a building in Edinburgh to low carbon design captured over a lifetime;
- The economic viability of retrofitting a commercial building to low carbon design in Edinburgh is very high;
- The benefit of rent increases is currently the main driver for low carbon retrofit;
- It is critical to enable a policy to mandate new commercial building to implement low carbon retrofit options and avoid the carbon lock-in effect;
- It would be beneficial to develop a standard or best practice for low carbon readiness design for commercial buildings.

Acknowledgement

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Technology and Performance of China Academy of Building Research Nearly Zero Energy Building

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The nearly zero energy building (NZEB) at the China Academy of Building Research (CABR) adheres to the design principles of "passive building, proactive optimisation, economic and pragmatic". An ambitious annual energy consumption goal of 25kWh/(m²·a) (including heating, cooling and lighting energy) was set during the design phase, without compromising building function and indoor environment quality. The demonstration project integrated best available building energy conservation technologies to create a signature NZEB project and to establish a foundation for development of China's NZEB standards.

This project adopted a high performance building envelope system to reduce its energy demand. An underground borehole and solar collectors serve the geothermal heat pumps and absorption chiller as the primary cooling and heating sources. Through smart use of renewable and traditional energy, building heating demand in winter is to be met with zero use of fossil fuels, and cooling energy consumption in summer will be reduced by 50%. In order to optimise operation and maximise energy conservation, various sensors and metering devices were installed to collect real-time operational data, and with the aid of the Energy Management System (EMS) and Building Management System (BMS), enable data monitoring, analysis, and control improvements. This paper introduces the ideas and technologies of China Academy of Building Research Nearly Zero Energy Building (CABRNZEB) in building design, energy plant and renewable energy application. Real energy consumption data and indoor environment analyses over two years are presented.

Keywords: Nearly zero energy building, passive design, operation data

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Background

Global energy demand from buildings is projected to grow by 838 Mtoe till 2035 compared to 2010 (IEA, 2012). Reducing energy consumption in the building sector is one of the most important measures for global energy use reduction and climate adaptation. Net Zero Energy Building (NZEB) has gained increasingly wide attention over the last few years and is one promising path to further energy conservation in future building development. Passive design, proactive measures with renewable energy sources are recognised as strategies to help realise energy savings in buildings (Zhang *et al*., 2016).

At present, domestic and international development of passive ultra-low energy buildings has become a new trend. Research on design methodologies, technologies, monitoring methods and the evaluation process has been carried out by either researchers or project consultants. Cao *et al.* (2016) offered a brief overview of state-of-the-art approaches in zero energy building (ZEB) technologies and pointed out that climate change significantly impacts building energy performance. He suggested that the building envelope and ventilation play a role in reducing energy consumption and to realise ZEB. Zhou *et al.* (2016) published articles on the operational performance of a "net zero energy building" in China, in which they presented the challenges of nearly zero energy building development, and gave suggestions for nearly zero energy building to realise the design target in China. Ahmad *et al.* (2016) focused on available technologies for building energy metering and environment monitoring in nearly zero energy building and analysed their advantages and disadvantages. Shen *et al.* (2016) presented the first study on thermoelectric technology applications in NZEB, and the study shows that the system could satisfy cooling and heating requirements very well, and improve annual solar generation by 767kWh (34%). It provides a new way to apply thermoelectric technology in NZEB. Zhang *et al.* (2016) presented the operational performance of ground source heat pumps in CABRNZEB.

The technology path to achieve ultra-low energy consumption and zero energy buildings includes: precision in forecasting building load and energy consumption; passive design to reduce the load; high-performance energy systems; maximising the use of renewable energy; and building energy consumption monitoring and debugging. In the building's energy systems, heating and air conditioning systems account for a significant proportion of building energy consumption and is a main target for energy saving. It is an important area for improving energy efficiency and to maximise the use of renewable energy technologies to attain ZEB.

Several renewable energy utilisation methodologies, high technics, and advanced systems have been applied in CABRNZEB. This paper presents the design concept, technology applications and operational energy consumption of CABRNZEB; popular technologies and energy systems adopted in low energy buildings in China; and conclude with valuable passive and active design methodologies and technologies for ZEB in China.

Introduction to CABRNZEB

CABRNZEB is a 4-storey office building with a floor area of 4025m^2 and occupancy of approximately 180 full-time employees. CABRNZEB is a demonstration building of the U.S.–China Clean Energy Research Center program (CERC) on building energy efficiency. The aim of this demonstration building is not only to meet a requirement of the CERC project but is also a representation of CABR's decades of research in the field of building environment and energy.

The project will address fundamental issues about building energy efficiency in China. CABR's demonstration building is an attempt to achieve NZEB at an affordable cost. The experience acquired from the CABR project will be valuable input to the development of future Chinese standards and a roadmap towards NZEB. Adhering to the design principle of "passive building, proactive optimisation, economic and pragmatic", this demonstration project sets the ambitious annual energy consumption cap of 25kWh/(m^2.a) (including heating, cooling and lighting) with a pleasant indoor environment.

On 11 July 2014, Secretary Moniz from the Department of Energy (DOE) in the U.S. and Minister Wan Gang of Ministry of Science and Technology of China officiated at the opening ceremony of CABRNZEB (Figure 1).

Figure 1 Opening ceremony of CABRNZEB

Figure 2 Aerial view of CABRNZEB

Figure 3 Front view of CABRNZEB

Introduction to Design and Technologies

Design

Passive Design

Under the principle of passive design and proactive optimisation, the building construction strictly followed requirements for a passive house in terms of high performance insulation, air tightness, and insulation etc. Specifically, an environmentally friendly method was considered in the design stage, and implemented.

High performance insulation: The whole building was insulated with an excellent insulation material called vacuum insulation panel (VIP). The panel has a thickness 1/10 that of regular insulation materials but with 10 times the thermal conductivity efficiency. The U values and other parameters of the building envelope are shown in Table 1 below.

Table 1 U values and other parameters of the wall and roof by measurement

位置	Inside wall temperature	Outside wall temperature	Thermal resistance	U value
	(°C)	(°C)	(㎡ •K/W)	(W/㎡.K)
North wall	16.7	3.7	4.05	0.24
Roof	17.6	3.4	6.18	0.16

Air tightness: Air tightness is heavily emphasised in a passive house. A stable indoor heating and cooling load, with controllable energy consumption could be achieved in houses with good air tightness, otherwise extra energy is required for air heating or cooling resulting from infiltration. The installation of windows and doors was precisely done in the construction period to avoid infiltration. A special installation method and high quality air-tightness products were employed, such as air barrier products and powerline 540 sealing. Figures 4, 5 and 6 show an air barrier wrapped around a window, a rough opening wrapped with an air barrier and finally sealing the gap with powerline.

Figure 4 Airtight window under construction

Figure 5 Airtight window under construction

Figure 6 Airtight window under construction

Windows: The window system is particularly important for a low energy building. Either the U value or the installation method determines the air tightness, insulation properties, natural ventilation, daylighting and other properties. Triple-pane windows with vacuum layer were installed with intelligent shading added inside south facing windows. The shading can be adjusted in response to solar intensity and incidence angle. Low-E film was applied; it has very good light transmission performance and prevents heat entering the building. The whole heat transfer coefficient of the window is less than 1.0W/(m^2.k), and the shading coefficient is less than 0.2W/(m^2.k).

Figure 7 Window system

Daylighting: To increase indoor lighting comfort, the internal walls of second and fourth floors were constructed of glass (Figure 8), so daylight can enter into corridors, decreasing the requirement for artificial lighting in public areas and enhances viewing comfort. The design also satisfies the light performance comparison with the first and third floors.

Figure 8 Natural lighting

Solar tube: Solar tubes have been widely used in building design to enhance the utilisation of daylight. Its linkage to artificial lighting control is an interesting research topic in academia. A solar tube combined with an auto-shading window system were installed in the fourth floor conference room. Research on the control methodology of the solar tube and artificial lighting is carried out in this room. Light of approximately 500 lux could be measured on the surface of the table on sunny days (Figure 9). With the combination of solar tube and artificial lighting, about 20% energy saving in lighting could be achieved.

Figure 9 Solar tubes (outside and inside)

Other Environmentally Friendly Features

Roof garden: Designers constructed a roof garden on the top of western side of the building (Figure 10). Flowers and grass were planted to provide views and a place of relaxation for employees. More importantly, this could also decrease the cooling load in summer to some extent.

Doors: New energy saving concept design can be found at the main entry of the building. Two layers with different orientation were designed to avoid air infiltration during winter.

Permeable floor: Open areas around the building have a permeable floor constructed with water permeable materials. It is very effective for groundwater conservation and provides a very good floor surface on rainy days, especially during rainstorms.

Figure 10 Roof Garden

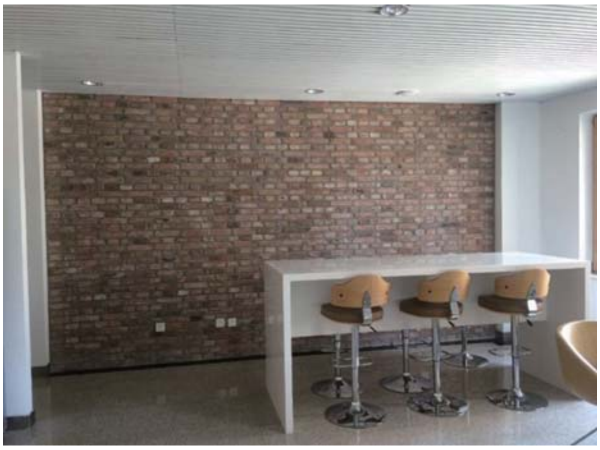

Figure 11 Cafeteria

Material use: A wall of the coffee bar was decorated with waste building bricks (Figure 11).

Proactive Optimisation

High performance heating ventilation air conditioning (HVAC) equipment: Several types of high efficiency or high performance equipment were employed in this building, including heat recovery units, ground source heat pump (GSHP) units, absorption chiller, variable frequency pumps, and high-precision valves.

Renewable energy: Solar thermal was introduced to provide cooling in summer and heating in winter. A ground source heat pump acts as one of the most important energy systems for the building. A distributed grid-connected photovoltaic (PV) power system was adopted in this project (Figure 12), with spontaneous self-use, mainly for the internet. The total installed capacity is 2.88KWp. The total power generation was approximately 37.5MWh in 2014. The PV system is also used to serve public area lighting if required, and additional electricity generated is used for the internet.

Figure 12 PV panel system

Lighting: LED and fluorescent lamps were installed on different floors and two control brand with several control methodologies are applied on different floors and to different lamps. Power over Ethernet (POE) with LED is applied and tested in one office on the fourth floor. In this connected lighting system, every luminaire is directly connected to and uniquely identified in the building's Information Technology (IT) network. This allows system managers to monitor, manage and maintain individual light points via a lighting management software. This system is the second application of POE in the Asia region and demonstrates great research value for application of direct current in the lighting system.

Energy System

By achieving a minimal heating and cooling load, and a pleasant indoor environment, the energy system is a hot research topic in the passive house or NZEBs. CABRNZEB's energy system design and operation was an exploration of integrated design and is expected to provide an effective solution for the design of energy systems for NZEBs in China.

Ground source heat pump (GSHP) has been developed for more than 30 years in China and successfully applied in different projects due to its high performance and environmental benefits. It is one of the best choices in areas with balanced heating and cooling demand. Solar cooling and heating have been applied in a few demonstration projects in China in recent years. However due to low energy density, instability, and poor economy, it has not been widely applied. In low energy building, with excellent thermal performance and low cooling load, the scale of solar heating and air conditioning systems can be reduced thereby improving its economy. With sufficient regenerative properties, it also makes solar heating and cooling systems more reliable.

To maximise the utilisation of renewable energy, improve energy efficiency and to explore new solutions for nearly zero energy building, a combined solar thermal and ground source heat pump system was adopted. The energy system is shown in Figure 13.

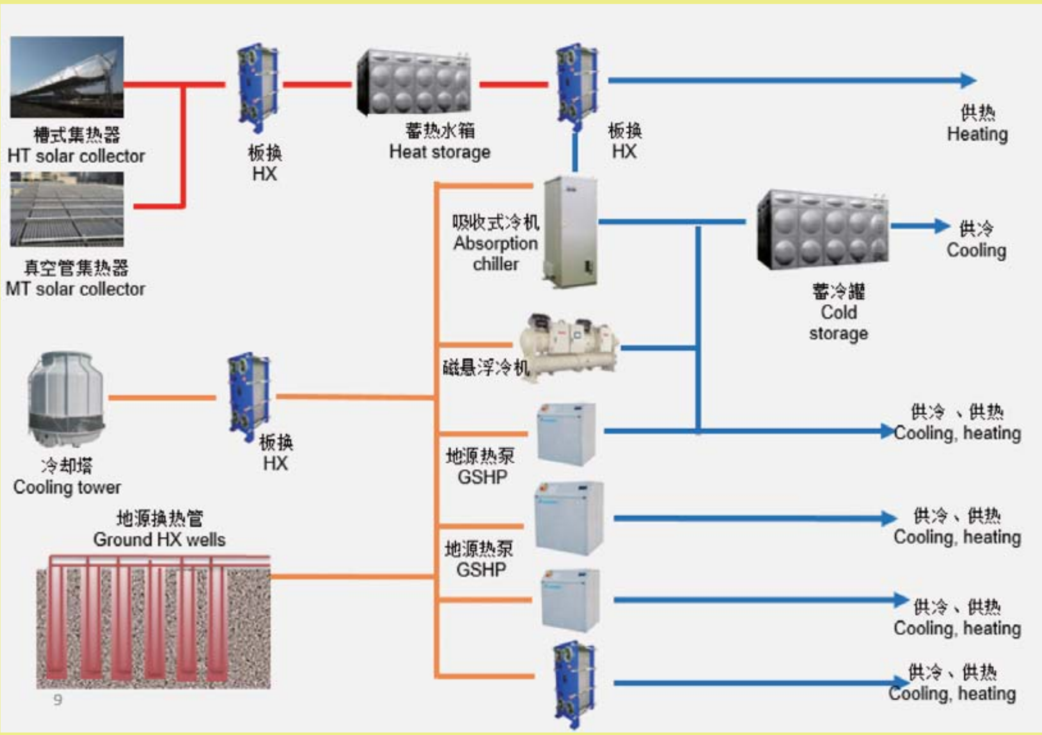

Figure 13 Energy system of the building

It is composed of 6 HVAC terminals: radiant ceiling, radiant floor, fan coil units (FCU), Variable Refrigerant Volume (VRV), water loop heat pump, radiator (Figure 13).

One absorption chiller and two GSHP units are the main energy system in the building. The absorption chiller, driven by two types of solar collection systems (Figure 14 and Figure 15) is recognised as the largest solar thermal air-conditioning system providing the ventilation load in Asia. This is supplemented by a 50kW GSHP unit in summer. The other 100kW GSHP unit meets both heating and cooling demand from the radiant terminals on the second and third floors. Coupled with ground source heat pumps, the solar collection system provides direct heating in winter with thermal storage. The organisation of the energy plant is shown in Figure 16. The energy plant is very well organised with each equipment and pipe orientation tagged with different colors.

Figure 14 High temperature solar collector

Figure 15 Median-temperature solar collector

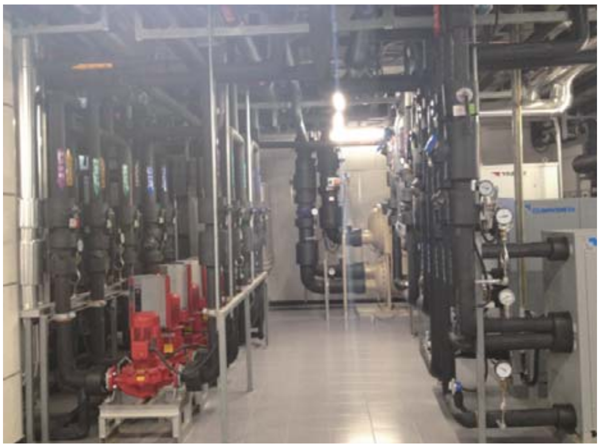

Figure 16 The energy plant room

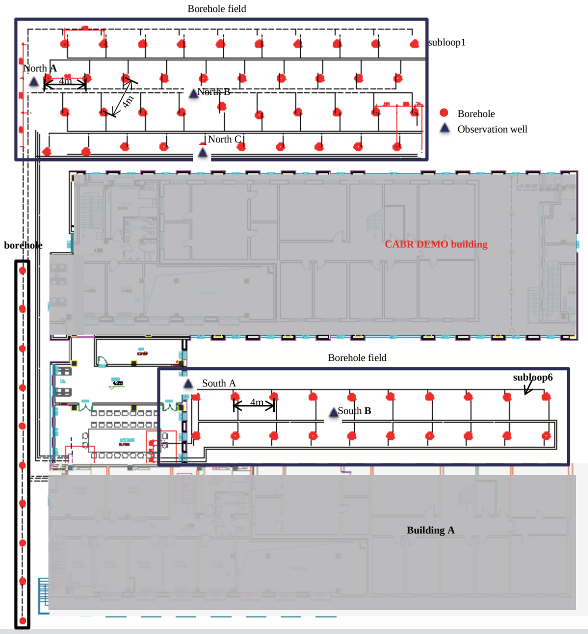

Figure 17 Borehole distribution

Borehole distribution is illustrated in Figure 17. 70 boreholes are located in the open space of the building site—with 20 for double U-tubes with 100 metre-depth to the south, and 50 for single U-tubes with a depth of 60 metres to the north and west. These boreholes are grouped in 7 sub-loops and ground water joins in a header before entering the building. Water flow is balanced by balancing valves and monitored before being distributed to different units.

Five observation wells were drilled, considering soil temperature variations, to monitor the impacts from summer operation of the GSHP systems. Three wells were drilled at the boundary of the borehole field and two were drilled in the middle where temperature sensors were placed inside the wells at 10–15 metre intervals along tube depth.

Intelligent Elements

There is comprehensive indoor environment control for particulate matter (PM2.5), carbon dioxide (CO_2), Volatile Organic Compounds (VOCs), temperature, humidity and noise. More than 1000 I/O points were integrated into the Building Automation (BA) system for optimal operation of the energy system to maximise energy savings. To demonstrate cutting edge technologies and to promote NZEB, the newest information and communications technology (ICT): including wireless sensor network (WSN), radio frequency identification (RFID), computer vision, machine learning and wireless communication are applied (Figure 18).

Figure 18 Intelligent technologies

Building Energy Management System (BEMS)

A complete and precise building energy management system was constructed, to monitor energy consumption and more importantly, to facilitate optimal operation of the building. The Building Automation System (BAS) (Figures 21–23) was constructed and integrated with the BEMS (Figures 19 and 20) to control operation of the lighting system, building energy plant and HVAC terminal systems, and to monitor indoor and outdoor air environments. More than 2000 points are monitored and controlled by this system.

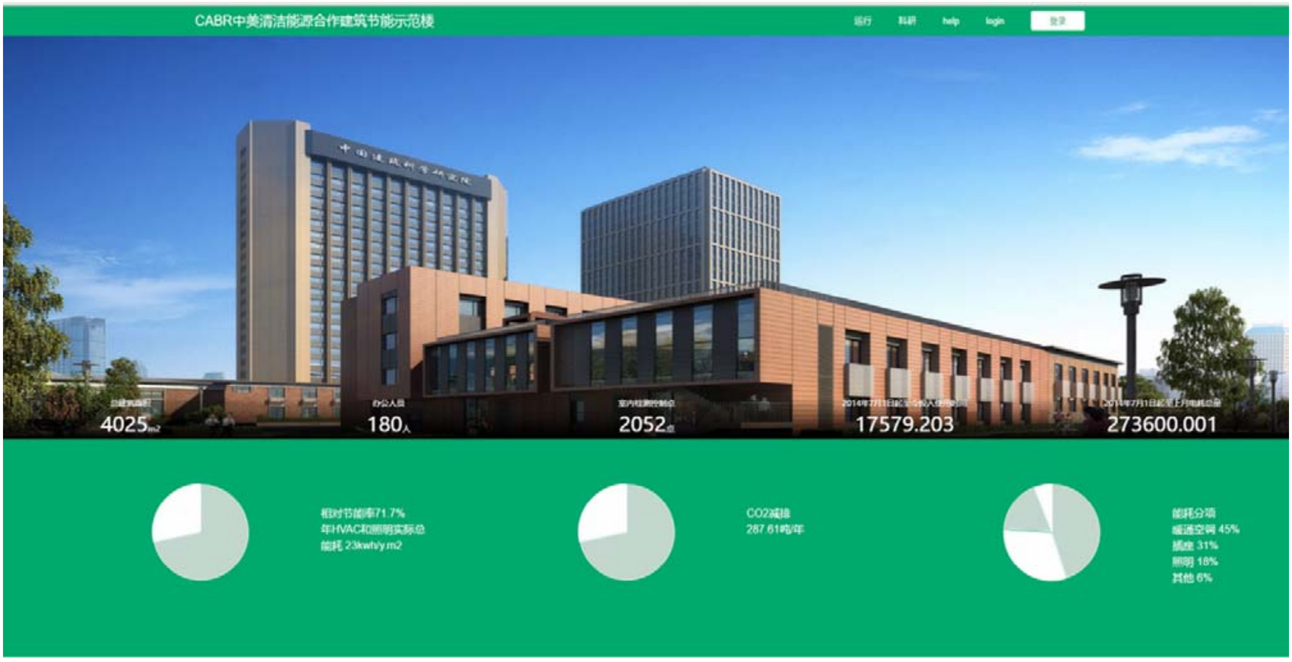

Figure 19 Interface for BEMS data analyses

Figure 20 BEMS website

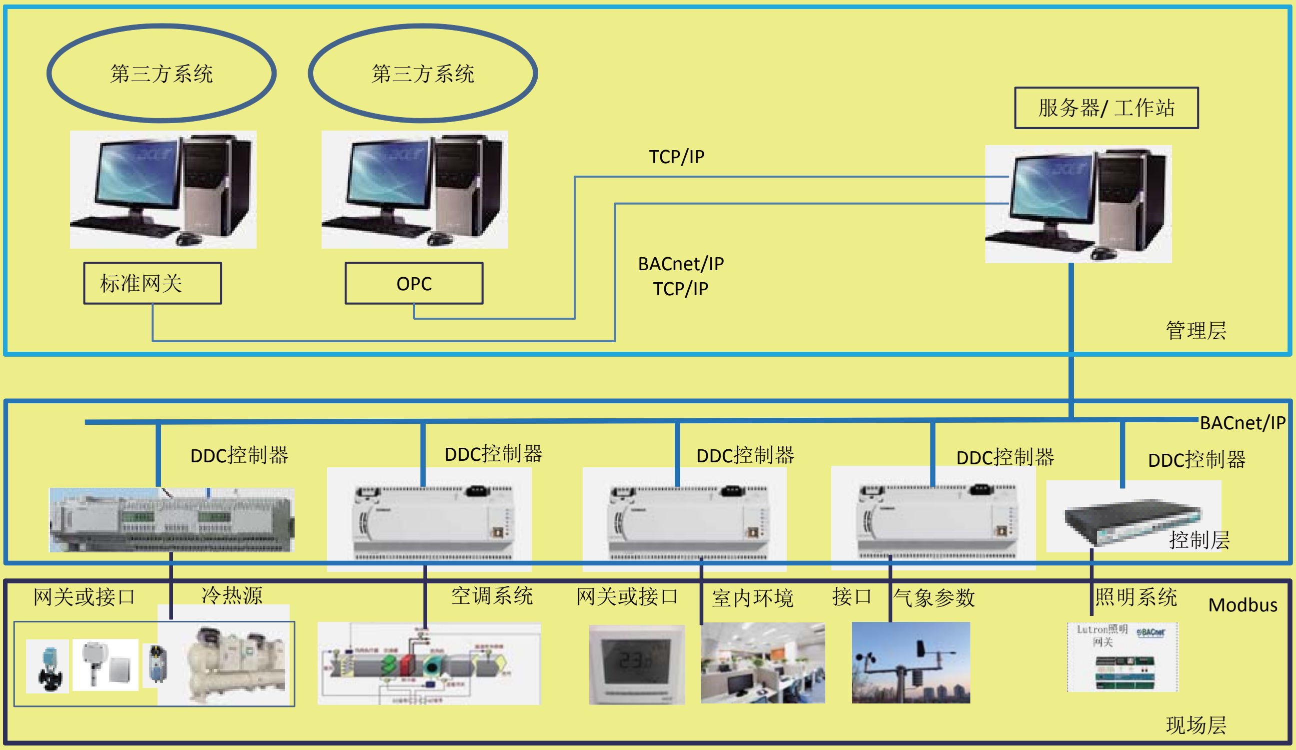

Figure 21 Construction of BAS system interface

Figure 22 BAS web interface

Building Operation Data Analyses

Total Energy Consumption

This building opened in July 2014 and has been operating for more than 2 years. With proper building design, construction and operation, building energy consumption has achieved its original target of 25kWh (m^2.year) (including HVAC and lighting). Figure 24 shows the building's monthly energy consumption in 2015. Different colors show energy consumption items. Beijing

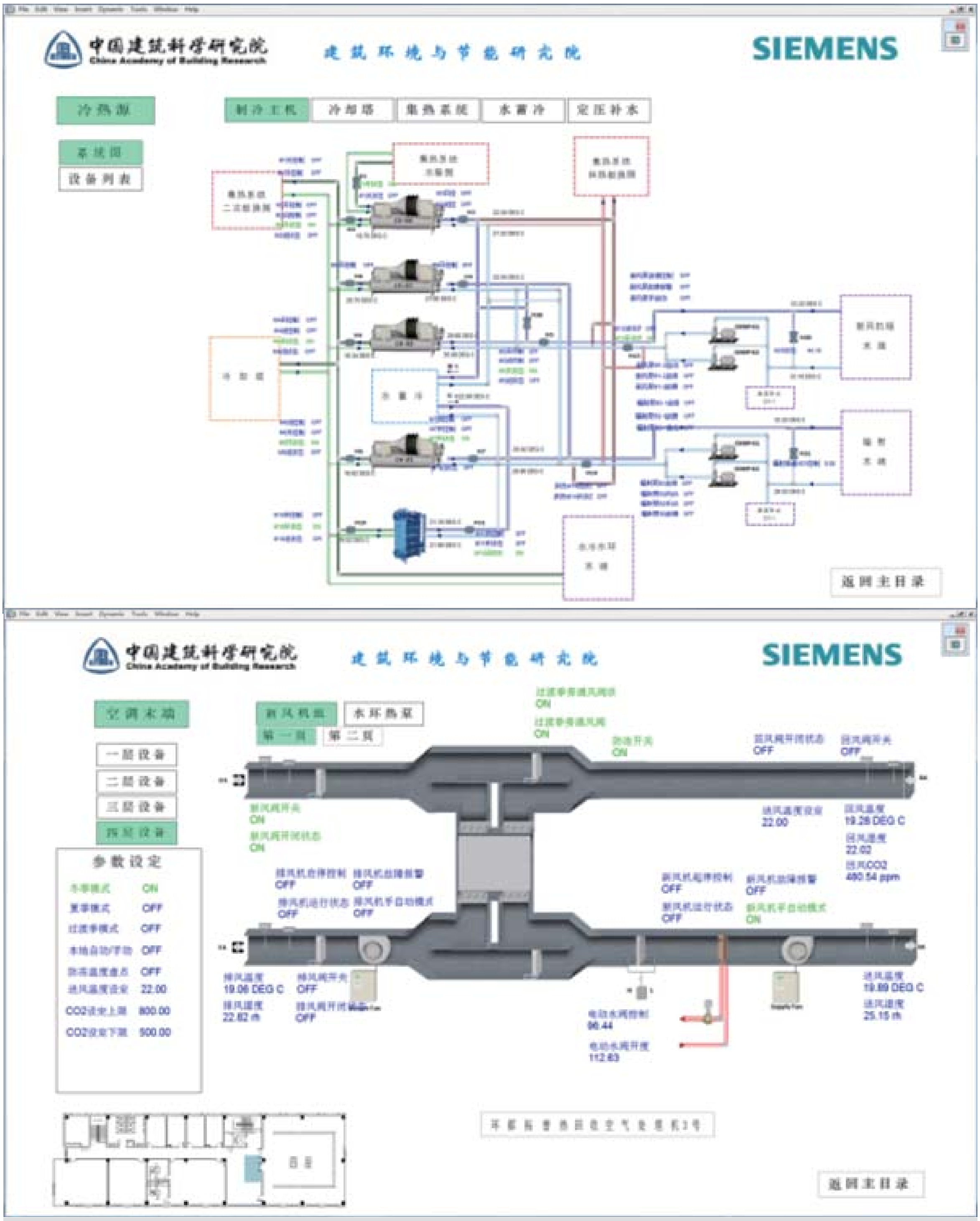

Figure 23 BAS energy plant and air conditioning terminal control interface

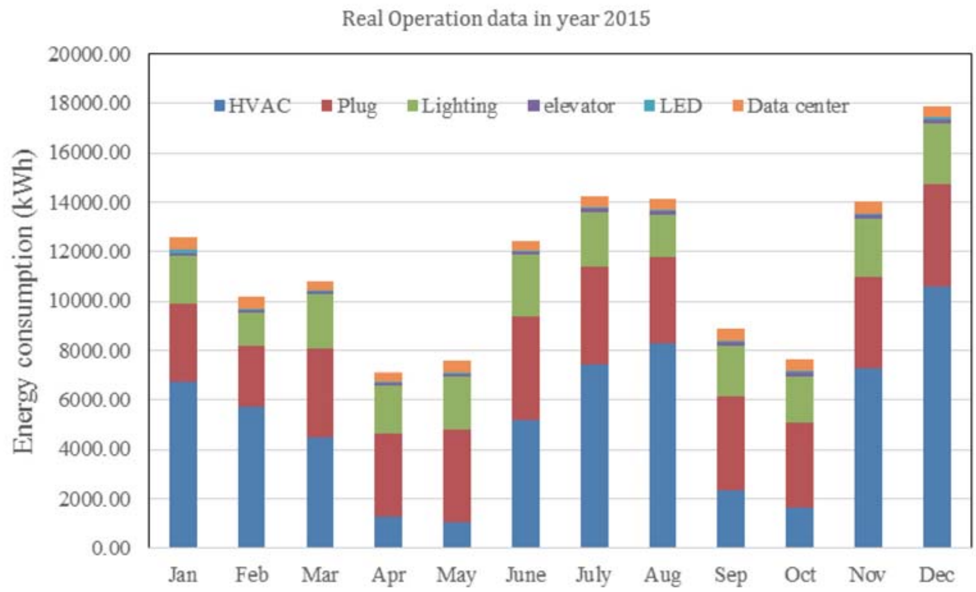

Figure 24 Monthly energy consumption of the building in 2015

has 4 distinctive seasons. The cooling period starts from June and ends in September while the heating period starts from November to March of next year, so highest consumption appears in July, August and December and lowest demand is in April, May and October. The total energy consumption in 2015 was about 137,494kWh and equivalent to 34kWh/(m²·yr). The energy consumption of the average office building (except heating) in Beijing is about 111.2kWh/(m²·yr) (Wei *et al.*, 2009) which is nearly three times the energy consumption of CABRNZEB (including heating). This building could be a milestone in energy conservation in China, and it demonstrates that great energy savings could be achieved.

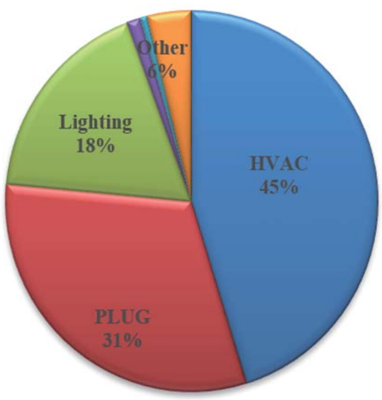

Figure 25 Distribution of energy consumption for the building

HVAC accounts for 45% of total building energy consumption. Plug load accounts for 31%, lighting accounts for 18%, while "other" accounts for 6%. It can be seen that targeting energy saving from HVAC is the most effective way of achieving overall building energy savings.

Annual energy consumption of actual building operation is shown in Figure 26. In 2014, HVAC and lighting energy consumption totalled about 27.67kWh, 10.7% higher than the design target. In 2015, there was a 13.7% decrease. Two probable reasons are:

1) The building was just completed in June 2014 and to provide a healthy indoor environment, intermittent ventilation through windows was allowed during the cooling period, while windows were strictly closed during the cooling period in 2015;

2) The mechanical system was put to use and the BAS underwent a debugging period in 2014. While the system was still under commissioning in 2015, the system performed in a more optimal condition, which resulted in higher energy savings.

Since CABRNZEB achieved a very high energy management and efficiency level, more energy saving is expected through consistent online commissioning and precise management in a building which has low energy demand and low energy consumption.

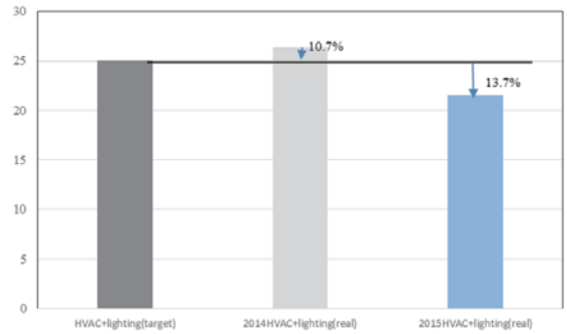

Figure 26 Energy consumption comparison between design target and actual consumption

Seasonal Energy Consumption

Summer season operation in 2014 was from 1 July to the end of September. In 2015, cooling operation was from 1 June to the end of September. Monthly energy consumption for the cooling season of these two years is illustrated in Figure 27, with blue representing the HVAC system and white representing "other". The data shows that monthly energy consumption in 2015 is lower than 2014 and average energy consumption is about 12000kWh or 3.0kWh/(month.m^2). This is 0.5kWh/(month.m^2) less than 2014.

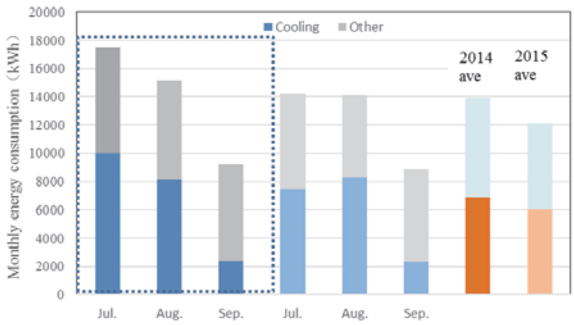

Figure 27 Summer season monthly energy consumption in 2014 and 2015

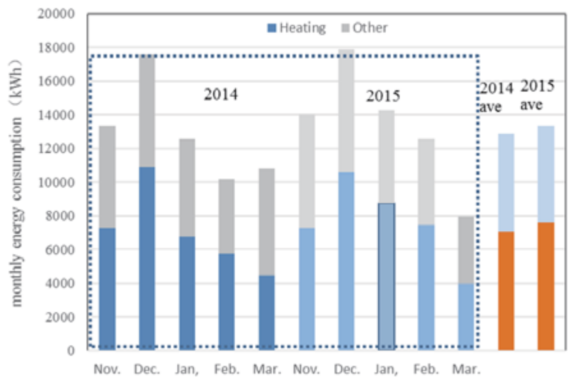

Figure 28 Winter season monthly energy consumption in 2014 and 2015

Figure 28 shows the building's energy consumption in the winter season in 2014 and 2015. Maximum energy consumption was about 4.3kWh/month.m^2 and 4.4kWh/month.m^2 in December 2014 and 2015, average energy consumption was 3.2 kWh/month.m^2 and 3.3kWh/month.m^2 in 2014 and 2015 respectively. Average outside air temperature in 2014 was about 3°C higher than 2015, suggesting that heating demand was higher in 2015, and maybe the main reason for higher energy consumption in 2015 compared to 2014.

Indoor Environment

Temperature and humidity sensors monitor the indoor and outdoor environment through the BAS platform. These environmental parameters are linked to the operational control of the energy plant.

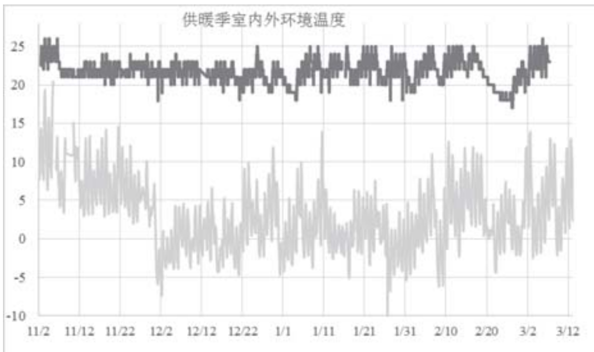

Figure 29 Indoor and outdoor air temperatures in winter season

Outside and indoor air temperature variations in winter are shown in Figure 29. Room temperatures were above 20°C in this period no matter how low the outside air temperature was except at the beginning of February, during spring holiday. In January, the indoor air temperature rose gradually and was above 23°C most of the time.

Figure 30 Indoor and outdoor air temperatures in summer season

Indoor and outdoor air temperatures in summer in 2015 are plotted in Figure 30. The highest outdoor air temperature was about 40°C, while indoor air temperature was a steady 26°C, which shows good air conditioning operation.

Indoor temperature is a critical parameter of chiller and HVAC terminal operation. Several different HVAC terminal systems are applied in this building, and their operational mode and chiller supply water temperature are adjusted according to indoor environmental parameters to realise energy savings. It shows good performance of the BAS platform of CABRNZEB.

Satisfaction Survey

An indoor environment quality and satisfaction survey was conducted. About 60 questionnaires were distributed to users. A total of 55 responses on the environment of the office was received. 71.4% of respondents were satisfied with the air quality. 28.5% of respondents were very unsatisfied. 45 questionnaires were received concerning the indoor environment and work efficiency. 100% of respondents felt the current indoor environment promotes work efficiency, while 28.58% of respondents felt very satisfied.

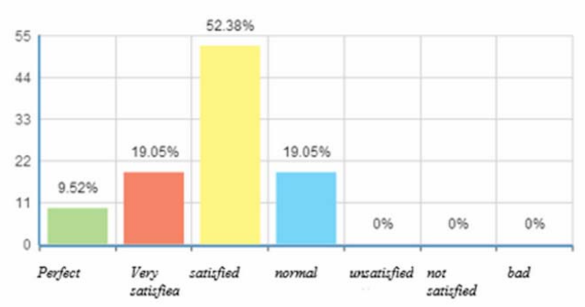

Figure 31 General evaluation of indoor environment

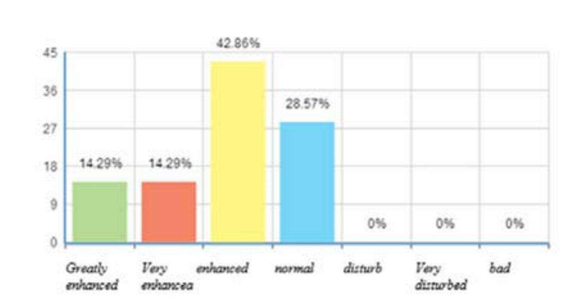

Figure 32 General evaluation of indoor environment on work efficiency

Conclusion

Building energy conservation in China has entered a new era after more than 30 years of development. Achieving low energy building design and operation call for integration of cutting edge technologies and scaling up such demonstration projects. CABRNZEB is the first pilot nearly zero energy public building in China and the first building which has a clear energy target and real operation data accessible by the public.

This paper gives a general introduction to CABRNZEB design features both passive and proactive including building envelope, air tightness, daylighting, and renewable energy applications. Solar thermal and ground source heat pump work together to provide heating and cooling for the building through different HVAC terminal systems. The Building Energy Management System and building automation system play essential roles in energy plant management and operation of the HVAC systems.

In monitoring the indoor environment, room temperature could be maintained above 20°C in winter, and a questionnaire on the indoor environment found a relatively high level of satisfaction among building occupants. From analysing 2 years of operational data, energy consumption in HVAC and lighting was found to be about 23kWh/(m^2.yr), which is 8% lower than the original energy consumption target. The operation of CABRNZEB is just in the early stages. With ongoing operation, the overall low energy consumption of the building is valuable for future research.

Acknowledgments

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NZEB Best Practices in Canada — A Residential Case Study in the Cold Climate

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There is a growing demand for zero-energy residential housing, which is not only energy efficient, but also able to supplement the energy requirement with onsite renewable energy generation. The typical approach is to greatly reduce energy demand through a climate optimised building envelope, to lower energy consumption with innovative heating, ventilation and air conditioning (HVAC) system set-up, and achieve the net zero-energy building (NZEB) goal by supplementing the energy deficit with renewable energy.

This paper explores a well-referenced residential house—the EcoTerra™ house as a case study, and showcases the different technologies and strategies deployed to the house. The materials presented in this paper are drawn from a variety of sources where different groups have done thorough research on this innovative residential zero-energy house.

The results indicate that NZEB is, in fact, feasible to build with commercially available technologies, and the performance is well-tested with many years of proven operation. The technologies and strategies presented in this paper should equally well be applied to houses at other locations which share similar climatic characteristics.

Keywords: Net zero-energy residential house, integrated building design, renewable energy generation, building-integrated photovoltaic-thermal system, passive solar heating

Bruno Lee is an Assistant Professor at the Department of Building, Civil & Environmental Engineering (BCEE), Concordia University. He specialises in building energy performance simulation and focuses in employing different simulation techniques to study the performance of the built environment in an integrated manner. His research areas cover robust high performance smart building, integrated building design through co-simulation, stochastic optimisation of energy and durability performance, and BIM-based automated energy performance simulation.

Rana Habibi is a building engineering Masters student at Concordia University. Trained as an architect, her research facilitates the architectural decision making process in the early design phase by developing a workflow that automatically generates a proliferation of building design options to enable visualisation of the morphological form-finding process.

Introduction

Building energy efficient houses should rather be a practice than a goal. This is the mandate behind the EQuilibrium initiative of the Canadian Mortgage and Housing Corporation (CMHC) to demonstrate the potential in building next generation energy efficient and sustainable houses. Therefore, all houses built under this initiative deployed only commercially available systems to ensure that the successful formula can be replicated by other builders. The EcoTerra™ house is one of the twelve nominated projects under the EQuilibrium initiative. The initiative promotes the use of healthy building materials and finishes, passive solar heating and cooling, energy and resource efficient construction, energy efficient appliances and lighting, natural daylighting, integrated systems, water conservation, land and natural habitat conservation, and sustainable site design, all according to the climate and site specific situation (CMHC, 2007b). This paper mainly focuses on energy performance and illustrates how different technologies work in combination to achieve the NZEB goal. The objective is to promote holistic integrated design and building practice.

Project Description

EcoTerra™ house is a two-storey detached single family house located in Eastman, Quebec (about 100km east of Montreal). The two-storey residential house (234m²) includes a living room, dining room, kitchen, and powder room with laundry on the main floor. There are two bedrooms, an office, and a full bathroom on the second floor. The basement is unfinished with an open space and a mechanical room. Figure 1 (CMHC, 2007a) shows the exterior of the EcoTerra™ house.

Figure 1 The south facing exterior of the EcoTerra™ house (CMHC, 2007a)

Canada, particularly the eastern provinces, is in a cold but relatively sunny climate, where both passive and active solar systems are suitable choices for NZEB (Chen *et al*., 2010). The house is connected to the grid to facilitate energy balance throughout the year.

In subsequent sections, different systems and how they interact together are demonstrated with a particular focus on building integration of solar technologies and distributed thermal storage. The design goal is to optimise the use of solar energy for heating while minimising overheating. An overview of the technologies is presented in Figure 2 (CMHC, 2007a).

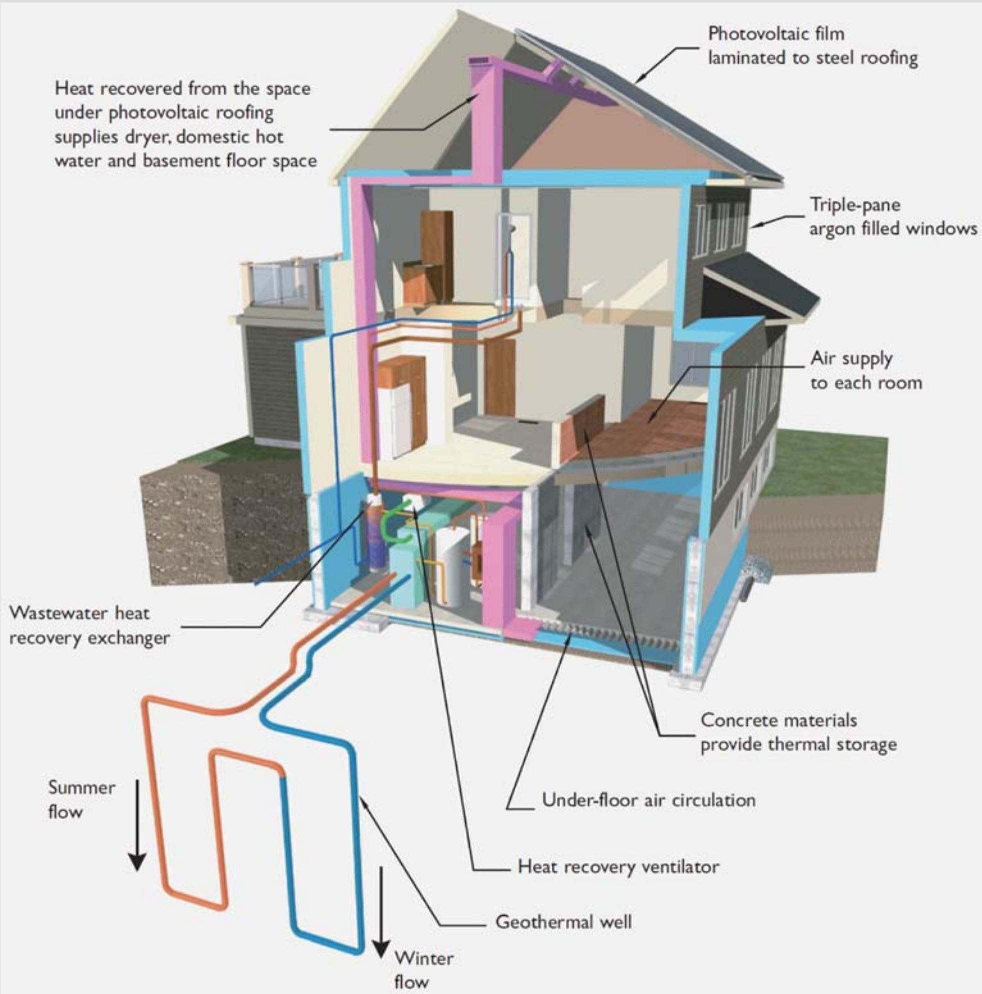


Figure 2 Innovative technologies deployed at the EcoTerra™ house (CMHC, 2007a)

Energy Demand and Passive Measures

Energy demand is curtailed with a highly insulated airtight envelope. By properly sizing the windows and choosing the thermal properties, the solar heat gain is distributed and stored in the thermal mass to reduce space heating demand and avoid overheating. A 1m^2 skylight located above the staircase helps to spread natural daylight to the kitchen and dining area. There are windows in every space except the north facing part of the basement.

Building Envelope Construction

EcoTerra™ envelope assemblies are prefabricated off-site at the manufacturing facility to ensure quality and promote buildability. According to CMHC (2011a), the house can be closed-in in 3 days on site since the delivered assemblies are completed with drywall, insulation, windows, and even wiring.

Two types of spray-in-place foam insulation are applied:

- Low-density, semi-flexible polyurethane foam with an open-cell structure (thermal resistance: R_{SI} 0.66 per 25mm of thickness) which offers good acoustic performance;

- Low-density, rigid polyurethane foam with a closed-cell structure (thermal resistance: R_{SI} 1.05 per 25mm of thickness) which provides structural integrity. The closed-cell acts as an air barrier if applied on the outside and as vapor barrier if applied on the inside of the assemblies. There is no need for extra air and vapor barrier membranes. The wall assembly is depicted in Figure 3 (CMHC, 2011a).

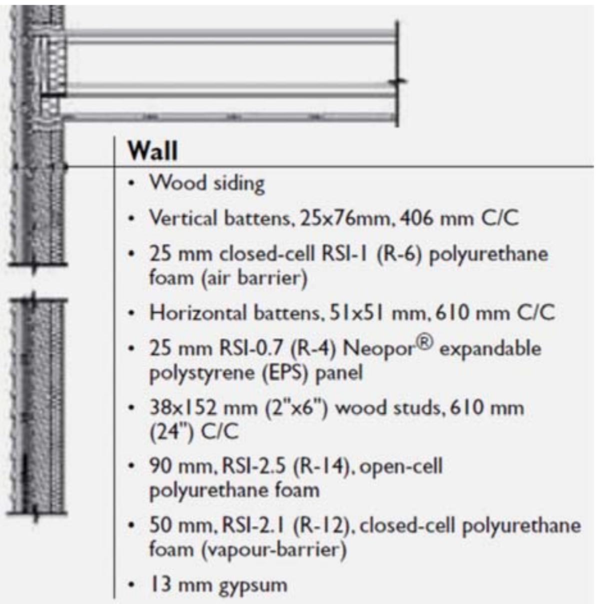


Figure 3 Construction details of the wall assembly (CMHC, 2011a)

The whole building enclosure is very air tight with highly insulated envelope assemblies. The thermal resistance values are rated as:

- R_{SI} 9.5 for the roof
- R_{SI} 6.3 for walls above grade
- R_{SI} 4.2 for the walls below grade
- R_{SI} 1.3 for the basement slab

The result is highly insulated walls that are 38% more energy efficient than standard walls and 22% more efficient than the Novoclimat standard in Quebec (CMHC, 2011a).

Windows and Shading

EcoTerra™ house is situated in the northern climate and capitalised on potential passive solar heating with the main glazed façade facing south. On the south façade, 21m^2 (33% of the surface area) is glazed. This directly benefits the family room with an open space concept to promote daylight penetration. On the north, east, and west façades respectively, 0.6m^2, 6.7m^2, and 5.2m^2 are glazed.

With such a proportionally large glazed area, overheating from excessive solar heat gain during the summer can be a major problem. This can increase cooling energy demand if not properly designed. EcoTerra™ house is fitted with overhangs and motorised blinds to mitigate the problem. Additional shading is provided through motorised awnings for the second floor south facing windows and west facing patio door.

To minimise heat loss, triple-glazed, low-e coated, argon-filled operable windows in vinyl frames with thermal breaks are used. The effective thermal resistance value is R_{SI} 0.77 with a solar heat gain coefficient (SHGC) of 0.5.

Thermal Mass

EcoTerra™ house adopts a passive solar heating concept which relies on thermal mass to absorb the solar heat gain during the day to prevent overheating and to store the heat for later release through the night. The arrangement minimises temperature fluctuations.

Thermal mass is mainly deployed in the family room and basement where there are sizable glazed areas. The concrete floor in the family room is a 15cm thick concrete slab. The solar absorptance of the brown colored ceramic tiles is around 0.6~0.7 to promote absorption of the solar gain into the concrete slab. There is a 1m tall and 0.3m thick concrete wall divider (see Figure 4, CMHC, 2010) that separates the family room from the kitchen.

Figure 4 Ceramic tiled concrete floor and a concrete wall divider (CMHC, 2010)

Ventilated Concrete Slab (VCS)

The south side of the basement is fitted with a VCS, which is a 12.5cm layer of concrete on top of a steel deck (see Figure 5, CMHC, 2011b). Under the steel deck are the air channels where heated air drawn from the building-integrated photovoltaics thermal (BIPV/T) system (to be discussed in the next section) are passing through. The slab is 11m long and 3.6m wide. The extra length offers long enough contact to allow the heat to be absorbed into the concrete before being exhausted to the outside. The VCS is strategically located in the basement to avoid additional structural support for the family room installation and to promote extraction of heat due to the lower temperatures in the basement. Solar gain through the basement windows is also absorbed into the concrete from the top (see Figure 6, CMHC, 2011b). The heat will be slowly released back to the basement during the night hours. A layer of insulation is placed under the steel deck to ensure heat do not escape to the ground.

To promote heat transfer from the heated air when air is passing through the air channels, the air velocity is intended to be kept in the range of 0.8m/s to 1.5m/s. This is achieved by carefully designing the number and size of the air channels with cross-sectional area that can receive the optimal amount of air flow from the BIPV/T. The amount of concrete is designed to release the heat back slowly and maintain the surface temperature below 29˚C to avoid discomfort on the feet.

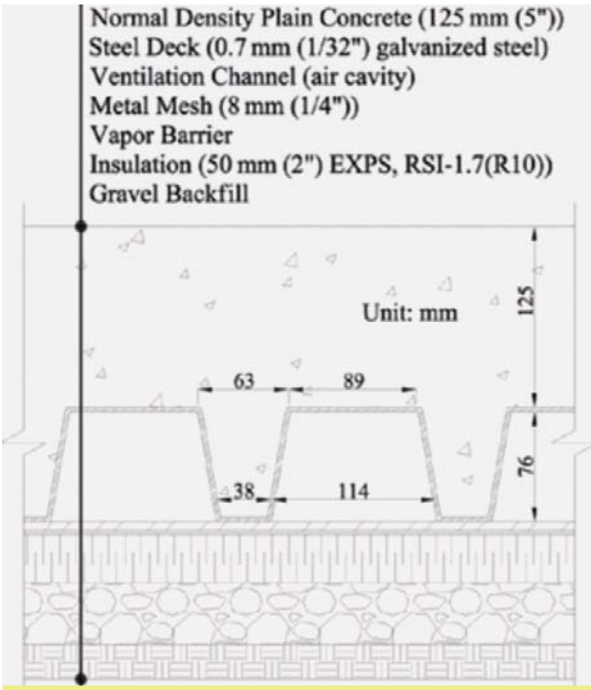


Figure 5 Cross-section of the VCS (CMHC, 2011b)

Figure 6 Placement of the VCS next to the basement windows (CMHC, 2011b)

Energy Generation, Storage, and HVAC Systems

Multiple systems serving different purposes are deployed and integrated in a seamless manner for optimal and efficient operation. The main HVAC system is a forced-air system, which works together with a geothermal heat pump, to allow heat gain to be distributed effectively from the source (e.g. BIPV/T) to the location of use (e.g. basement space).

Building-integrated Photovoltaics Thermal (BIPV/T) System

BIPV/T was installed on the roof. "Building integrated" implies the panels themselves are part of the building envelope (in this particular case, it acts as both metal roofing and roof sheathing) and not as stand-alone elements attached to the roof; Figure 1 shows the seamless integration of the panels on to the roof. The BIPV/T system generates electricity with a PV array of

2.86kWp made up of 21 amorphous-siliconfilm sheets (each rated at 136Wp at a size of 2.7m²) laminated to the metal roof oriented to the south and sloped at 30°. The power is sent to a DC/AC inverter and the system is connected to the utility grid through an electric meter for net metering where energy surplus is exported to the grid while energy deficit is drawn from the grid. The BIPV/T system can generate an estimate of 14.6kWh/m² of electricity, which almost fulfills all the electric energy needs of the EcoTerra™ house. Installed in 2008, the system has a conversion efficiency of 6% only. Recent offerings of BIPV/T modules has much higher efficiency (double or triple that of 6%) and could easily make the house a net generator of electricity.

The BIPV/T system also heats the air through an open-loop solar thermal collector with a length of more than 6m. As heat is extracted by the collector; in effect, it cools down the temperature of the PV and thus increases the PV's efficiency. The air drawn through the system is heated and distributed to spaces through the integrated insulated HVAC ductwork.

The design is highly dependent on the temperature and air flow rate at the outlets, which in turn depends on solar availability. Effective use of the heated air at various temperatures and flow rates to raise the overall efficiency of the system is definitely a topic of interest; the EcoTerra™ system applies the heated air in three ways (illustrated in pink lines in Figure 7, Chen *et al*., 2010):

- Space Heating - the aforementioned VCS is heated by the air from the BIPV/T, it has been estimated space heating needs is reduced by 16kWh/m² (IEA, 2010).

- Domestic Hot Water (DHW) - during non-heating season, the heat is diverted to fulfill the needs of DHW at an estimated 6kWh/m² (IEA, 2010).

- Clothes Drying - the heated air could be drawn into the dryer by operating the dryer in fan mode. The occupants will be informed through a building information display when the BIPV/T air is higher than 15°C and less than 50% relative humidity (RH).

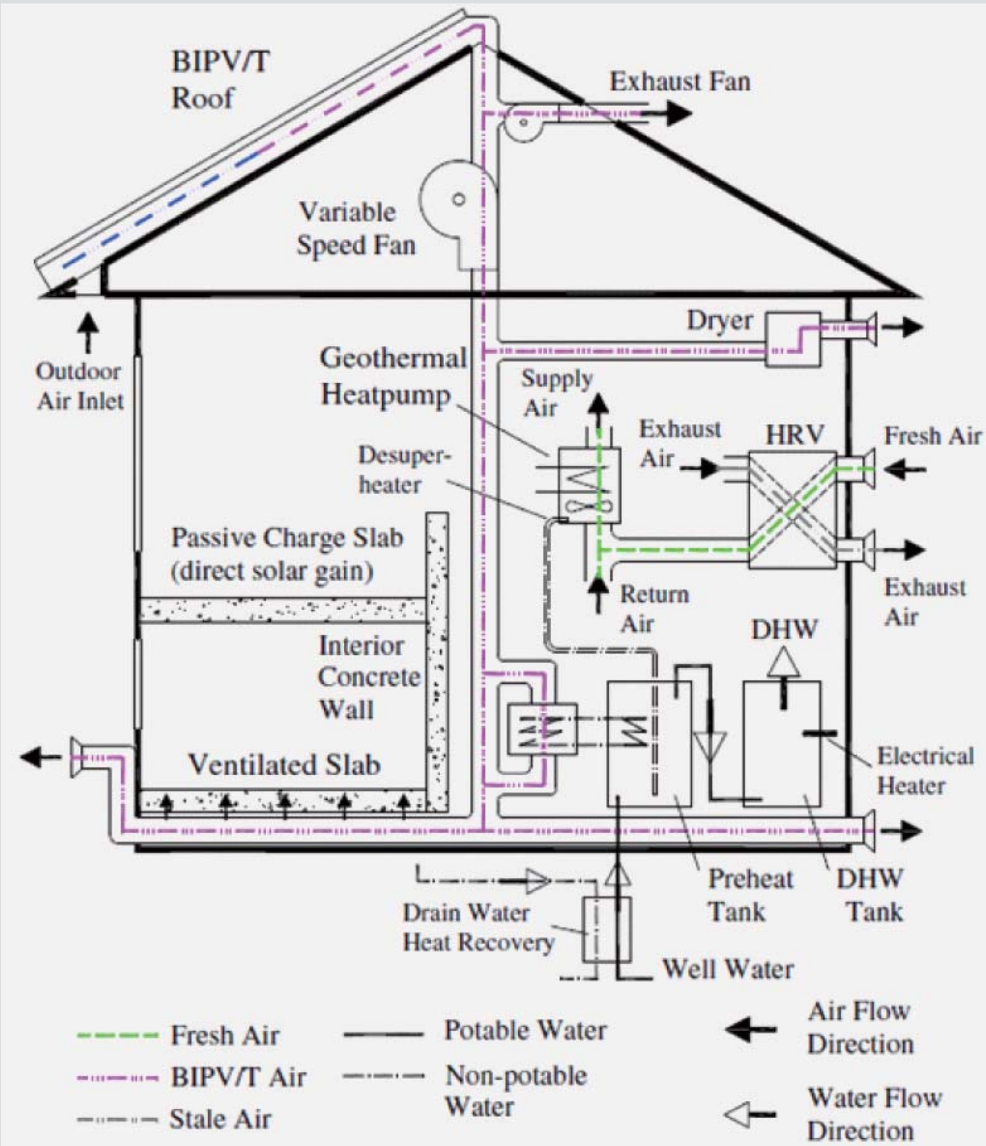
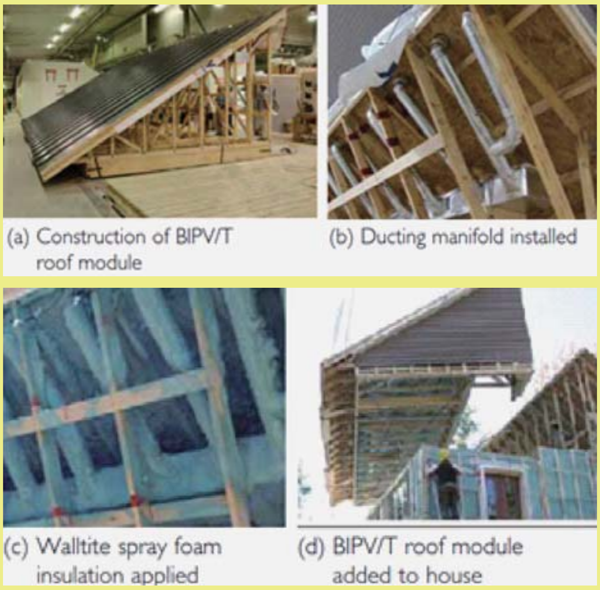


Figure 7 Applying thermal energy of the heated air from BIPV/T (adapted from Chen *et al*., 2010)

The EcoTerra™ BIPV/T assembly was prefabricated off-site at the manufacturing facility. Since the whole setup is not common, off-site prefabrication by skilled labor mitigates potential on-site workmanship issues. The supporting structure of the BIPV/T is fitted with outlet holes at the top and air inlets at the bottom. Spray foam insulation acts as both thermal insulation and air barrier, and provides additional structural support to hold the BIPV/T system and ductwork in place. This additional structural support is important as the whole assembly is prefabricated and transported a long distance to the site. Figure 8 (CMHC, 2011c) illustrates the construction of the BIPV/T module.



(a) Construction of BIPV/T roof module
(b) Ducting manifold installed
(c) Walltite spray foam insulation applied
(d) BIPV/T roof module added to house

Figure 8 construction of the BIPV/T module at different stages (CMHC, 2011c)

HVAC System

The majority of the energy consumption is in space heating and DHW. Passive solar heat gain fulfills around 40% of the heating demand, while the BIPV/T system offers an additional 10kWp of useful heat, and a ground source heat pump (GSHP) provides the rest. The outdoor temperature at the location can be very low during much of the heating season, therefore an air source heat pump is not considered to be effective. On the other hand, due to the rather stable temperature underground, auxiliary heating and primary cooling are provided by a 10.5kW two-stage GSHP with two vertical U-tube closed-loop heat exchangers connected in series. Heat recovery ventilator (HRV) also helps preheat or precool the fresh air intake (following the green line of Figure 7). The desuperheater of the GSHP provides heating for DHW at an estimated 3kWh/m^2 (Chen *et al*., 2010). Grey water heat recovery is installed and believed to be able to increase incoming cold water from 10°C to 24°C (IEA, 2010).

System Integration, Control, and Measurement

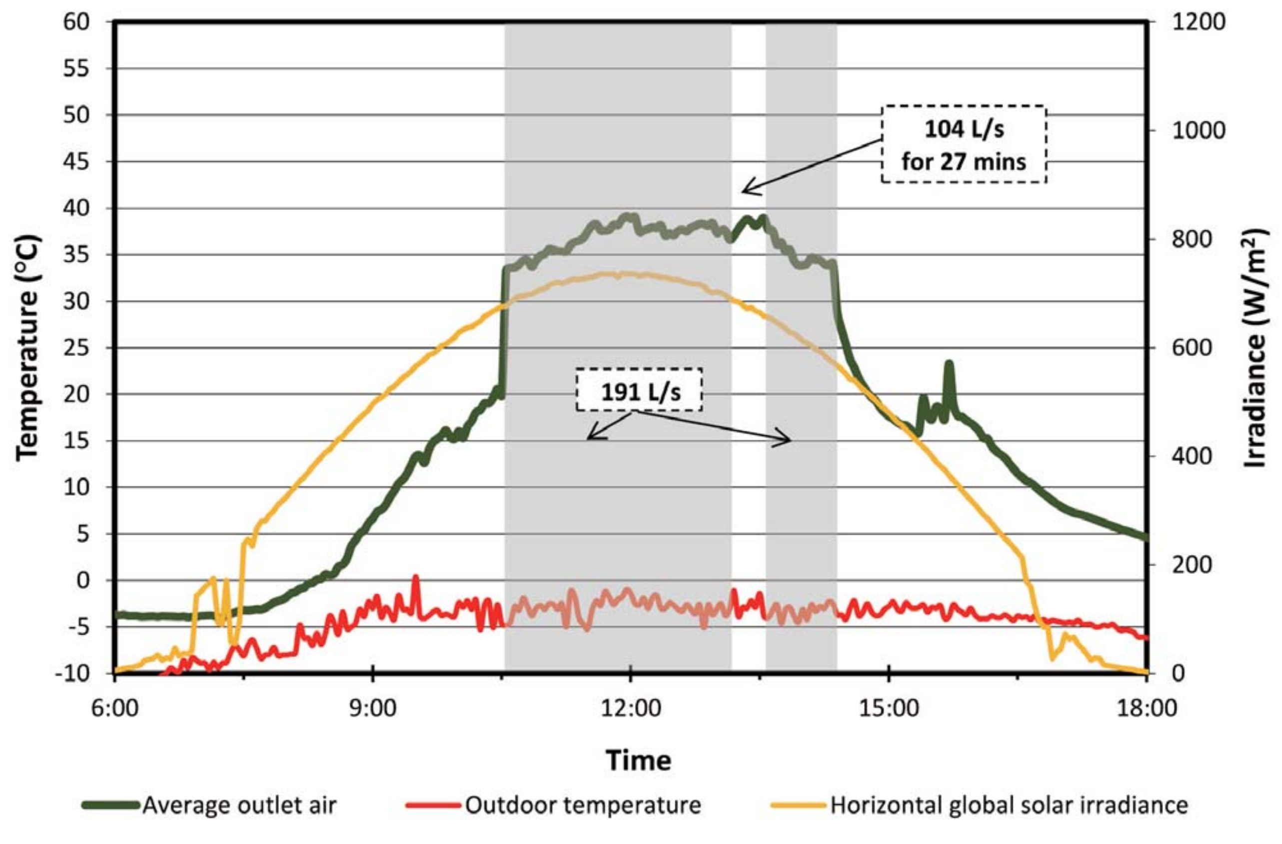
There are more than 150 sensors installed in the EcoTerra™ house collecting and storing data on temperatures, relative humidity, solar radiation, wind speed, energy consumption, etc. The measured data offers valuable insights into the performance of the building and allow complex control.

Energy Management Control System (EMCS)

To take full advantage of the different technologies installed, a centralised EMCS coordinates the operations of each of the following to optimise the energy performance of the house as a whole:

- Variable-speed drive for the BIPV/T with multiple motorised air flow dampers to control the air flow in the ductwork and for space heating to maintain the set point temperature;
- GSHP with a desuperheater for DHW and an electric heating coil for space heating if heating demand cannot be fulfilled;
- Fresh air control through HRV; and
- Motorised exterior awnings.

This is based on data from various temperature sensors on each floor, of the outdoor air, along the BIPV/T ductwork, and across the slab of the VCS. Figure 9 (adapted from Chen *et al*., 2010) shows the operation of the BIPV/T in relation to different temperatures and levels of solar radiation. The top chart in Figure 9 is data taken on March 17, 2008 which was a cold sunny day. The outdoor temperature hovered around -5°C. Through the length of the solar collector, the outlet temperature was able to reach greater than 40°C. It can be observed that the outlet temperature is highly dependent on the solar irradiance and less on the air flow rate. Because of the length of the solar collector, the outlet temperature could be fully developed and attained a temperature almost the same as the temperature of the PV metal surface regardless of the air flow rate. If the outlet temperature can be maintained at a high value, it is desirable to maintain a high air flow rate as well so as to extract more heat from the system.



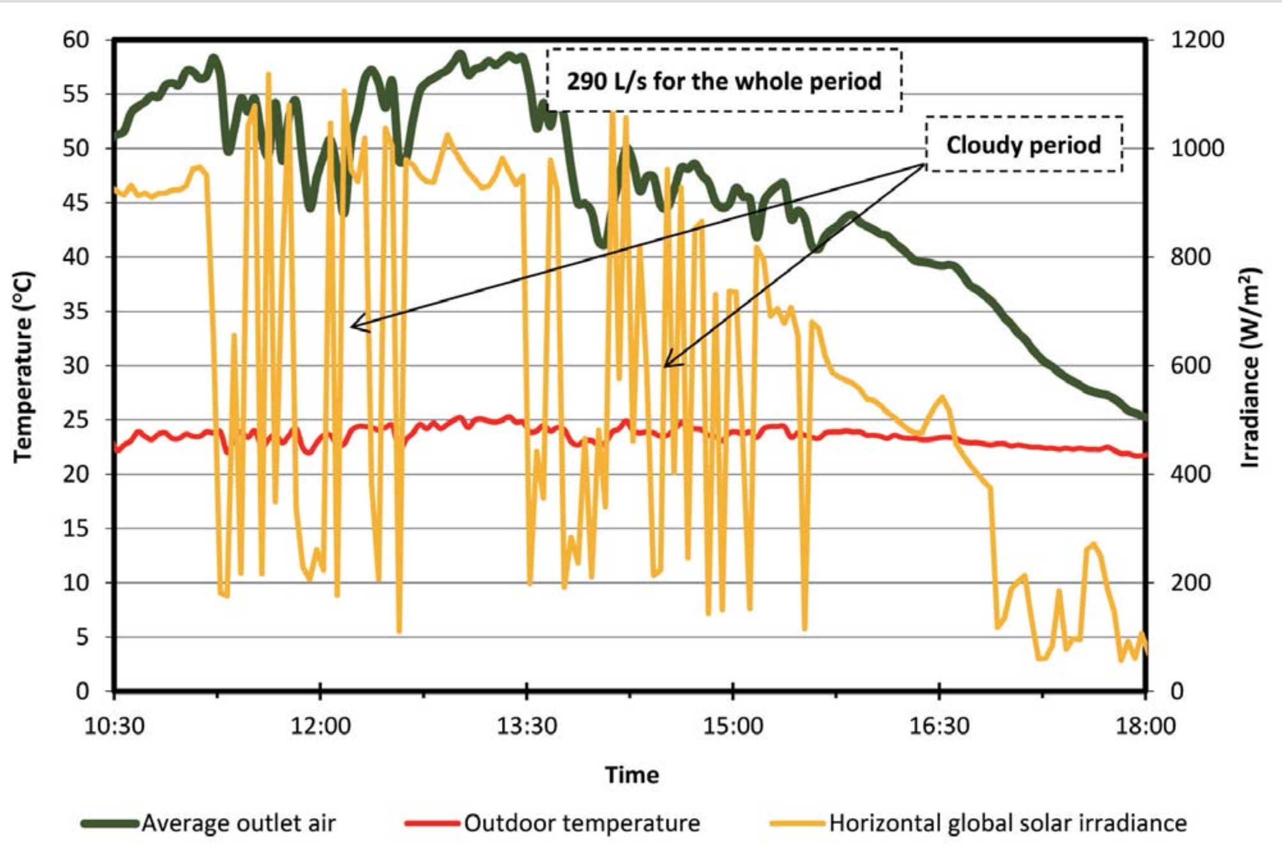


Figure 9 Relationship between outlet temperature, outdoor temperature, and solar radiation in March (top) and in June (bottom) (adapted from Chen *et al*., 2010)

By contrast, the bottom chart in Figure 9 depicts a warm but cloudy day on June 25, 2008. Solar irradiance dropped drastically on various occasions. As a result, the outlet temperature also dipped correspondingly.

Net Metering

The HVAC system demonstrates the complexity in coordinating a complex network of systems.

Current sensors installed at the PV inverter output allow the control system to monitor the amount of energy generated. Sensors installed at the dryer follow closely the state of operation of the dryer (or another piece of appliance) at any one point in time.

Figure 10 (adapted from Doiron *et al*., 2011) presents a typical energy balance during April 13, 2010. It shows profiles for both electricity demand and generation. It can be observed that quite a substantial amount of electricity was consumed by the heat pump during early morning hours for space heating. PV energy generation started to increase after sunrise and offset a significant portion of electricity consumption during the day. After sunset, PV ceased to generate electricity and electricity consumption is the highest of the whole day due to demands in using appliances and DHW.

Figure 11 (CMHC, 2007a) provides an overview of energy consumption and generation for a year. The utility company, Hydro Quebec, facilitates a net metering arrangement which allows a residential house to bank in credits for surplus electricity generation that could later offset the electricity consumption. The net annual energy balance for the EcoTerra™ house is only 13kWh/m^2. Such a comparison of annual consumption and production suggests that EcoTerra™ house has a very high potential to be a truly NZEB or even to generate more than it consumes.

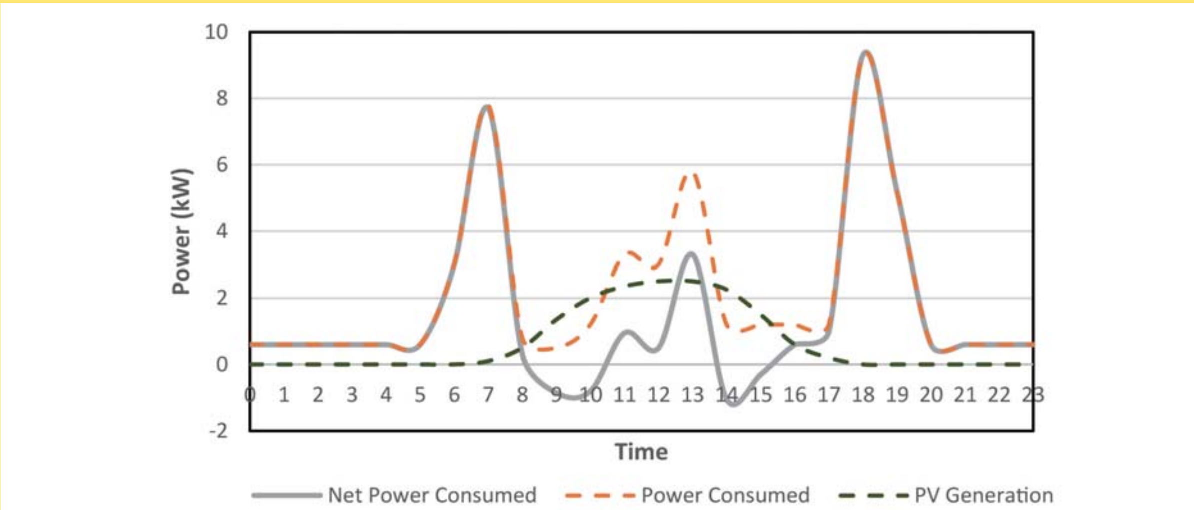


Figure 10 Electricity consumption and generation for a typical day (adapted from Doiron *et al*., 2011)

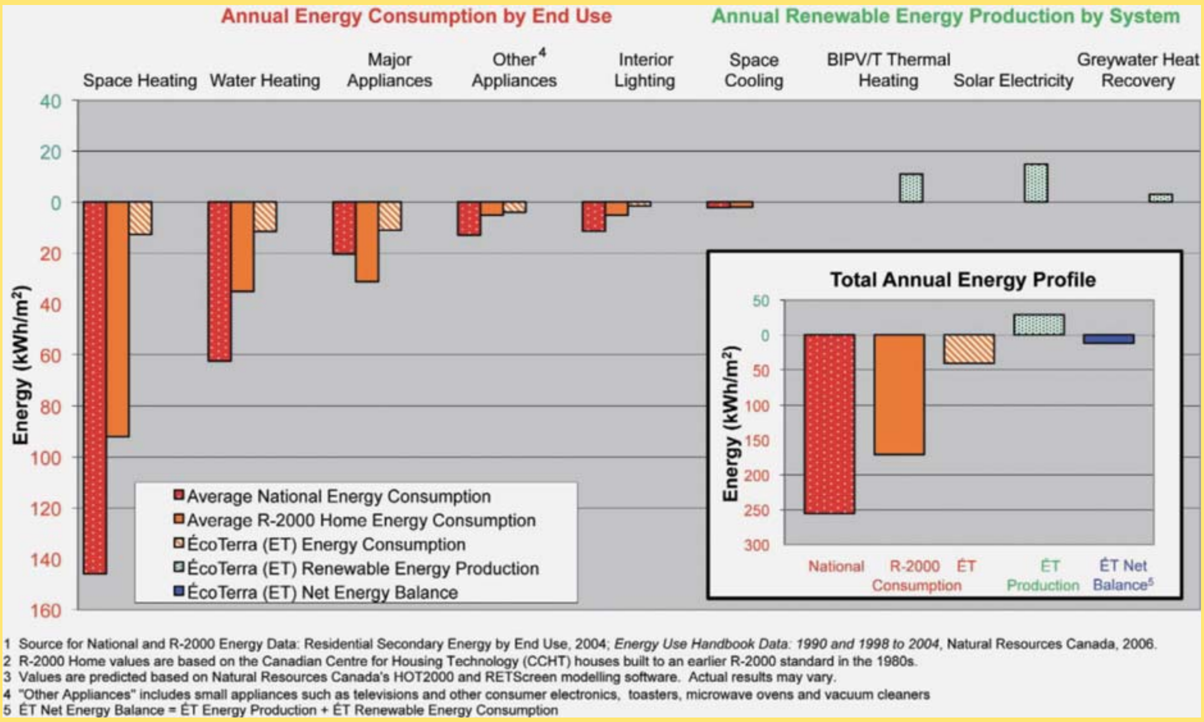


Figure 11 Annual electricity consumption and generation of the EcoTerra™ house according to energy end-uses and systems (CMHC, 2007a)

Discussion and Conclusion

EcoTerra™ house is a single family house where a family has been staying and living there for a few years. It is fully instrumented to collect actual performance data based on real operation of the occupants. The design goal of NZEB is almost achieved due to very aggressive energy saving measures. In fact, the building envelope plays a significant role in reducing energy demand by introducing passive heating and thermal storage and having a high thermal performance. As a result, space heating is around $10kWh/m^2$ compared to greater than 140 kWh/m^2 for an average Canadian home. Energy consumption for DHW is also drastically reduced to less than $12kWh/m^2$ from a national average of more than $60kWh/m^2$. PV electricity generation, BIPV/T thermal heating, and grey water heat recovery are the three major energy supply technologies that supplement consumption. As discussed, simply replacing the BIPV/T with newer higher efficiency panels will make the EcoTerra™ house a net energy generator.

The technologies presented in this paper are all commercially available products. Each of them is proven technology that has been on the market for a long time. What EcoTerra™ house has demonstrated is that significant performance gains can be achieved by combining these technologies into a well-thought-of system which offers the best overall efficiency. The BIPV/T example illustrates that that lack of skilled labor is still a major issue hindering the progress of the industry. Prefabrication and modular design can definitely help to solve the issue and improve the quality of the houses.

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Showcasing 'Real' Green Buildings: A Case for Post Occupancy of University Buildings

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Throughout their life cycle; from construction, operation to demolition, buildings contribute to environmental impact. Globally, there has been a shift towards adoption of green building policies, legislation, various programmes and rating tools for all new construction and refurbishment projects. While most of these policies and regulatory developments, including assessments have flowed through into office buildings; universities, particularly as building owner and occupier and operating in mainly urban areas are beginning to recognize the opportunities of following such policies for their own assets.

The University undertook a feasibility study to evaluate the actual versus expected performance of its two new 5 Star Green Star accredited buildings: Building A, housing business related disciplines; and Building B, housing built environment and related disciplines. The case studies were undertaken using a Post Occupancy Evaluation (POE) for monitoring building performance as the green star ratings are design intent only and do not reflect actual building performance.

A survey to understand the connection between the building user's outlook, and building operation and management, was undertaken using a Building User Studies (BUS) occupant survey. These evaluations were carried out in each of the two buildings to measure occupant satisfaction, complemented by internal stakeholder interviews, and energy performance data. This study showed that the buildings did not perform well in all aspects of the BUS survey, but performed well compared to other buildings at the University campus. A major source of dissatisfaction was the lack of engagement with the staff working in these buildings.

This study assists the University to evaluate how the buildings performed and the applicability and value of their existing green building standards. For the wider design community, analysis of the data highlights the importance of measurements to ensure optimization of the built environment, and recommending strategies for efficient management of buildings.

Keywords: Post occupancy evaluation, built environment, university buildings, Green Star, sustainability, building performance, Australia

Karishma completed her Bachelors and Masters degree in Environmental Studies and Resource Management. She has worked in private organisations on projects related to sustainable resource planning and forming corporate-community partnerships in Indian industries. She has also worked on projects related to energy efficiency measures in the commercial and residential building sectors in Australia.

She is currently pursuing a PhD in the field of sustainable buildings and their management. The aim is to enhance the overall energy performance of buildings (academic) by analysing the gap between actual versus expected performance. The research also looks at the impact of stakeholder engagement on project success and recommending strategies to close the feedback loop and establishing appropriate management frameworks in an organisation to achieve energy efficiency.

Usha started working in the field of energy efficiency and conservation since the late Eighties. This has now broadened to encompass sustainability issues in the built environment. She has worked in architectural practices in India, Canada and Australia, bringing practical knowledge of energy efficiency and conservation and triple bottom line sustainability to buildings and the built environment. Usha brings wide industry experience to her teaching and research. Usha is colead of the Sustainable Buildings and Construction Programme, 10 year Framework of Programmes on Sustainable Consumption and Production. She has been invited as key note speaker and invited speaker at National and International Conferences. She has been involved as an expert in panel discussions for Australian government and industry and as sustainability advisor/Board member for various built environment peak bodies in Australia.

Matthew is experienced in leading multi-disciplinary, multi-cultural design and engineering teams and has enjoyed building business opportunities through motivating and empowering inter-disciplinary teams in Australia, China, Hong Kong, Philippines, and the USA. He is one of the twelve active committee member of the Property Council of Australia's Future Trends committee providing advice on the 'new' and 'next' of property innovation trends for Australian property investment businesses. Matthew also sits on the Standards Australia sub-committee for Indoor Air Quality working to develop an Australian standard for air quality within our built environments. He is currently working on measuring occupant productivity and well being in relation to overall building performance.

Introduction

With increasing globalization and population increase worldwide, attention is turning to the significant role buildings play in contributing to harmful emissions to the environment. In addition to reducing building emissions, climate adaptability of new and existing buildings is also critical for mitigating climate change effects on the built environment, particularly in urban areas. As a result, incorporation of renewable and sustainable features in the built environment has become one of the major foci for policy planners and the design community, including building operators.

Tertiary academic institutions generally manage extensive land and building portfolios and have a wide range of schools/departments (built or refurbished) that increasingly need to comply with sustainable design principles. After the implementation of principles of sustainability and climate change, the management of the performance of university buildings throughout their life cycle must be monitored appropriately for ensuring optimal outcomes for all stakeholders. These academic institutions have a high ratio of direct users (staff, students and building managers) involved. They have potential for showcasing themselves as best industry practice models as they nurture future generations of building designers, planners and managers.

This research studies and compares two newly constructed sustainable buildings (Green Star rated buildings) at a University in Australia. The aim is to study the benefits of incorporating green planning, design and construction in these two buildings, and to understand the significance of appropriate building performance and management practices for mainstreaming into the design, construction and operation of university assets.

The University has committed to including sustainability as part of its operations. It has signed up to a greenhouse gas (GHG) emissions reduction target of 25% by 2020 based on 2007 levels. It has also made a commitment to purchase 20% of the University's electricity from certified Green Power. The University has many buildings, both new and refurbished, which may be used to showcase examples of innovation and excellence as well as show commitment to sustainability and climate change on a larger scale. The two buildings included in the study are Building A (housing the schools related to business) and Building B (housing schools of built environment disciplines). The study examines the performance of these buildings with a focus on energy evaluation. Thus the study does not focus only on the intent to achieve sustainable outcomes from a design perspective, but also on the actual performance of the buildings, focusing on energy as a major criterion underpinning sustainability outcomes.

This research, therefore, aims to understand the disconnect between the design and performance of a building which is uncommon in standard practice in the industry. Industry usually focuses on design intent for sustainability, rarely do studies undertake post occupancy to understand whether design intent has been met. The objective of the study was to investigate the significance of evaluating occupant satisfaction and using the respective POE data to facilitate performance management of the buildings involving property and asset management support. Broader outcomes include the development of clear assessment mechanisms for establishing links between performance measurement and performance management at micro and macro levels with an understanding of how occupants view its value and what lessons can be gleaned from this exercise for both the university and the design and build community.

Green Star Education Rating Tool

Green Star has a brand reputation in Australia. It is a certification system, and has a similar foundational basis to similar types of rating schemes worldwide such as LEED (Leadership in Energy and Environmental Design) (USGBC, 2015) and BREEAM (Building Research Establishment Environmental Assessment Method). With more than 428 projects certified, Green Star assesses and rates against a range of categories aiming to encourage leadership in environmentally sustainable design and construction, showcasing innovation in sustainable building practices, and considering occupant health, productivity and operational cost savings.

The Green Building Council of Australia (GBCA) 'Value of Green Star' report of 2013 stated that on average, Green Star certified buildings produce 62% lower GHG emissions, use 66% less electricity than conventional buildings and use 51% less potable water than average Australian buildings. The report also found that Green Star - As Built certified buildings recycled 96% of their construction demolition waste, compared with the average recycling rate for new construction projects of 58% (GBCA, 2013). Green Star may be used for a range of different building types, including educational institutions.

To achieve Green Star certification, buildings are judged on various aspects. Those relevant to understanding how a building operates are management, Indoor Environmental Quality (IEQ), energy criteria including factors such as building commissioning, building tuning, building guides, occupant satisfaction, IEQ parameters, GHG emissions etc. These factors evaluate how buildings are intended to be managed during operation. Hence, as the study focuses on performance management of buildings involving building users, Green Star buildings serve the purpose of understanding the buildings better. Building A scored a total of 13/14 under management criteria, 18/25 under IEQ criteria and 18/29 under energy criteria in the Green Star application originally submitted. Similarly, Building B scored 12/14, 13/25, 14/29 respectively in the three categories.

Post Occupancy Evaluation (POE)

Evidence shows there is a lack of a connection between the building user's outlook, how buildings are operated and managed, and the appropriate techniques for evaluating building performance. 'Evaluating the performance of buildings should be considered as an iterative process which acts as an ongoing process and extends to upgrading and refurbishment of buildings in occupation' (Green and Moss 1998, p. 36). One way to monitor building operations is Post Occupancy Evaluation (POE).

'POE over the years has progressed from a one dimensional feedback process to a multidimensional process that acts as an integrated element that can help drive the building procurement process further' (Hadjri and Crozier 2009, p. 33). The fact that POE is not an established part of the current management guidelines and framework as a mainstream activity reflects the historic obstacles to the building development process. It has been defined in several studies as, '… a process of systematically evaluating the performance of buildings after they have been built and occupied for some time (Preiser 2002, p. 42). It has also been defined as a 'Process of systematic data collection, analysis and comparison with explicitly stated performance criteria pertaining to occupied build environments' (Preiser *et al*., 1988), 'An appraisal of the degree to which a designed setting satisfies and supports explicit and implicitly human needs and value for those for whom building is designed' (Friedman *et al*., 1978, p. 20) and 'More holistic and process oriented evaluation' (Preiser 2002, p. 9).

General Benefits of POE

'By carrying out an evaluation of the building's performance after completion, commissioning and a period of use helps to find whether the buildings actually performed as they were supposed to do' (Derbyshire 2001, p. 81). POE helps to assess occupant's satisfaction and reactions, maintain appropriate management structures, provide inputs to regulatory processes, and helps to achieve operational targets.

POE has the potential to maximise building performance and thereby support social, environmental and economic or triple bottom line (TBL) benefits of sustainability. POE acts as a useful snapshot of users' views and 'assists in better understanding of the use and re-use of buildings over long life-cycles' (Whyte and Gann 2001, p. 460). POE can be explored architecturally, within realms of psychology, sociology and also technology, particularly where technology adoption is an issue. The most optimal time to undertake a POE is when sufficient time is given to the occupants to settle in the building in order to get appropriate results. This is usually a full year after moving into the building so that building services have operated over a whole year through different climate cycles (ASHRAE, 2013).

Involving users, and measuring their level of satisfaction with respect to various factors helps to obtain performance measurement results for a building, which when constructively utilized by facilities or building managers can assist them to affect change in a building. The results can assist facilities managers (FM) to continually test their strategies and meet organizational objectives, because 'whenever there is gap between the current results and FM's strategic objectives, there is an opportunity for improvement' (Amaratunga and Baldry 2002, p. 220).

By carrying out traditional and modified forms of POE, the study evaluates how changes in user behavior results in changes in the overall outcomes for building users and the technologies used in the buildings. By aligning occupants/users' perceptions to the primary design intent, there are opportunities to develop the link between the POE results for the buildings under study and also for the university.

'The overarching benefit from conducting POE is the provision of valuable information to support the goal of continuous improvement' (Zimmerman and Martin 2001, p. 169). Appropriate management or decision-making has a significant impact on implementation of POE and highlights its success within the facilities management framework. Thus in this research, the use of POE methodologies provides the ability for organizations to productively utilize users' feedback to help achieve building performance goals.

Gaps in POE Studies

The literature (for example, Kelly *et al*., 2005) shows particular aspects of thinking and personality that differ between simulation and reality or highlights the difference between the people who build models and those who actually use the space. By creating a bridge between the thoughts of building users and the way authorities manage the buildings is the core of this study. 'The main opportunity here lies in further innovation in the appropriate application of evaluation methodologies already existent' (Baird *et al*., 1996, p. xxi).

Previous research (Preiser *et al*., 2009) has highlighted the absence of scientific exploration of POE as a mainstream activity in the building procurement process. 'The rapid interest in POE quickly evaporated amidst various concerns and it became a subsequent failure to become part of an architect's normal services' (Cooper, 2001, p. 159). 'Distrust about the POE process from within the construction industry especially with concerns about the impact of POE on personal indemnity insurance has made the adoption of POE more challenging' (Cohen *et al*., 2001).

In buildings, distinguishing between an organization's and facilities management related issues has been difficult. The culture of the construction industry does not support ongoing learning and improvements at the same pace as for example, the Information and Communications Technology (ICT) industry. Typically, solutions are sought only when a failure is reported or needs to be investigated. Despite global interest in people's well-being and concerns of the quality indoor spaces and productivity, comparatively little advancements have been made in POE. A major barrier to POE is cost.

The design and structure of educational facilities is intended to shape the ways we think about education for the future (Radcliffe *et al*., 2009). In the 21st century, educational leaders are expected to understand how technologies can contribute to incorporation of sustainability elements in the design. This requires management structures and frameworks to be aligned with the organizational setting in order to support the design intention and overall infrastructural, psychological, social and philosophical objectives. There are many leading examples in literature showing such innovation and Building A explored in this paper is one such example, although this innovation is more prevalent in the commercial building sector than in the academic sector. Other notable recent examples in the non-residential sector in Australia, which have also undergone post-occupancy evaluations, include Council House 2 (Paevere and Brown, 2008), MLC Centre (BUS Methodology, 2015) and ANZ office Docklands (Alessi *et al*., 2014).

It is necessary to pave the way for the adoption of POE in the design and building industry so that buildings may be well managed to the original design intent. More collaboration is needed between architects, building designers and construction professionals as well as those involved in facility management and performance evaluation of buildings. To ensure the study stays within the scope, this research focuses on indoor environment quality of the workplace and the approach required to achieve the energy targets to optimize building performance. The users of the building are therefore the core stakeholders of this research.

Role of stakeholders

Stakeholders in universities are varied and it is worth examining this briefly. Stakeholder management is a critical component to the successful delivery of any project, programme or activity. A stakeholder is any individual, group or organization that can affect, be affected by, or perceives themselves to be affected by a programme (Bourne, 2015). University stakeholders may be quite diverse and a resolution of conflicting demands may be required for effective management.

Effective stakeholder management creates positive relationships with stakeholders through the appropriate management of their expectations and agreed objectives. Stakeholder management is a process and control that must be planned and guided by underlying principles and common goals. Stakeholder management within businesses, organizations, or projects should lead to the development of strategy utilizing information (or intelligence) gathered during common processes. The main criteria to understanding stakeholder management is to identify the stakeholders, prioritize them and understand their needs.

Methodology

The University is committed to improving sustainability across all areas of activities. Despite some of these buildings having received numerous awards, showing appreciation by the design community for their sustainability outcomes from theoretical perspectives, no practical evaluations have been carried out for the buildings.

Detailed evaluations of two recently constructed Green-Star rated buildings were conducted to observe and evaluate performance in reality: Buildings A and B. Both are new buildings completed within two years of each other. The main types of schools housed in the buildings are different, as are their size, number of levels and volume. The key features of the buildings are described in the table below:

Table 1 Key features of the two study buildings

Features	Building A	Building B
Build Type	New Build (completed 2012)	New Build (completed 2010)
Faculty	Business related	Built environment related
Green Star Rating	5 Star Green Star (Design v1)	5 Star Green Star (Design v1)
Building Volume	52,000m^3	22,000m^3
Gross Floor Area	35,000m^2	13,000m^2
Number of Levels	15	7
Number of Occupants/Building Users (Staff)	Academic: 514 Non-academic: 175	Academic: 78 Non-academic: 41

The evaluations were conducted using two main methods: a Post Occupancy Evaluation (POE) using Building Use Studies (BUS) survey and stakeholder interviews.

POE provides a useful snapshot of user/occupant views, and assists in better understanding of the use and re-use of buildings over long life-cycles, in particular to enhance and achieve sustainable outcomes. The types of POE methods used in this study are as follows:

i. Questionnaires - using user satisfaction surveys (hard copy or online versions) to measure occupants' reactions and responses and standard BUS surveys measuring indoor environment quality;

ii. Walk in discussions with building users;

iii. Stakeholder interviews - semi structured interviews and open ended discussions were conducted with various stakeholders (facility managers, property/asset managers, and academic and professional staff) to understand the design intent, drivers for the sustainable shift, barriers faced throughout the process and lessons learned for future project success. The stakeholder interviews focused more on the process and role of management in the design, construction and operation of the two buildings.

The research activities are explained in detail:

Step 1: Post Occupancy Evaluation: Distribution of BUS surveys

The BUS survey has been applied in numerous research projects across the world for both residential and non-residential buildings (Arup, 2015; Leaman and Bordass, 2001). It is a 3 page survey and takes approximately 10 minutes to complete. The time involvement is critical to note. If surveys take too long, respondents will lose interest in undertaking the survey. A balance between the user's views and time required needs to be considered. The survey measured building user responses and reactions on overall building performance and their indoor environmental comfort.

Survey Format

The BUS standard has 63 questions in total. The survey measures provide a range of quantitative and qualitative responses pertaining to the perceived satisfaction of the occupants based on 12 lines of enquiry:

1. Occupant profile relative to age, sex, time in the building, time at desk, time spent on computer, workgroup size
2. Window seats and other basic information about the sample and the respondents
3. Ratings and feedback for design, needs, image, cleaning, storage, meeting facilities
4. Response times for key variables such as acoustics, travel etc.
5. Perceived productivity
6. Perceived health
7. Thermal comfort
8. Ventilation
9. Lighting, including glare
10. Noise, including interruptions
11. Furniture and space in the building
12. Other workplace performance variables including e.g. perceived control

It is worth noting that this standard survey format, particularly related to thermal comfort and ventilation areas, requires the building occupant to comment on their ability to individually control ventilation and thermal comfort. This level of control is often not provided in commercial facilities, therefore some additional survey interpretation is required.

The POE also analyzed building performance data (electricity, gas, water, temperature and occupancy rates) using data from the respective Building Management System (BMS). Collected data was compared to initial Green Star Educational Design v1 utility performance aspirations as determined by the Green Building Council of Australia (GBCA) in the educational design rating tool, and the wider university Campus building stock to assess building performance compared to other university buildings. Survey data was also cross-checked with the performance analysis and stakeholder interviews to triangulate outcomes.

Survey Response Rate

The survey was distributed as an online version to all academic and non-academic staff of the two buildings. The researcher followed up after a week. A hard copy was also given to occupants who found it easier to complete the survey at the time it was handed out. The overall response rate for the BUS survey for Building A was 20% and for Building B was 79%.

Step 2: Walk in Discussions

Walk in discussions were held with the academic and professional staff and building managers in each building after evaluation of the survey results to support a process of triangulation. This was done to cross check the results obtained from surveys regarding survey efficacy.

The findings from the survey suggested that the teaching and learning spaces are well utilized and liked, and the building image helps to elevate the overall institutional image. What did not work well for users was the lack of project related consultations and not being notified about the design intent and entire project delivery. Further concerns are the open space office planning creating noise pollution (affecting productivity, concentration and privacy) and storage issues. Some of the statements by users are as follows:

[The architects] culture and approach to design is one where they do put sustainability upfront within the design process…From a sustainability engineers perspective, that works in our favor as you know you are going to get that engagement early in the process and buy in. (Stakeholder 2, Building A).

If you don't get the design right the operational impacts are huge, they're massive. (Stakeholder 5, Building A).

Decent facilities (good natural light, security) and a good communal workspace, but flawed all round (Stakeholder 1, Building B).

The utilization stats from last year were 20% more attendance in the classes in the building than the rest of the university. (Building User 9, Building A).

Airflow, glare and noise can impeded concentration. Sometimes I might go elsewhere to work, otherwise the only option is to put up with it or find a workaround (standing fans etc.) (Building User 2, Building B).

As an exhibition venue it is very good, as a venue for office space it is moderately ok, as avenue for teaching it is very difficult (Building User 11, Building B).

The open office planning is terrible. It has affected my productivity greatly. It would have been better if the users were discussed in the design brief and the decision would have not been entirely management driven (Building User 7, Building A).

In many ways it is a beautiful building but the relentlessness of material pattern and harshness of materials used in interiors makes for a strange and ultimately dispiriting place to spend time in (Stakeholder 4, Building B).

A gap from other buildings had been that while the building technically had been delivered very well the actual occupation and transition into the building was something which was sometimes a bit lacking (Building User 2, Building A).

Noise issues alter how we conduct meetings, discussions, etc. Discussions of a private nature are very difficult to have. Security issues heighten levels of vigilance, make it difficult to have and do specific work, some staff + students do not feel safe working in the building (Building User 5, Building B).

I just think that if they just spend a bit more time closing out these things and making sure the monitoring is correct and ensuring the commissioning is done properly and doing sustainability more holistically it will be a brilliant building for the next 20 years (Stakeholder 3, Building A).

Step 3: Stakeholder Interviews

Interviews were conducted with key internal and external stakeholders (17 for Building A and 8 for Building B) involved in the design, construction and/or occupation of both the buildings. Stakeholders included the project manager, builder, architect, Environmentally Sustainable Design (ESD) engineer, building facilities manager, and senior managers, advisors, directors and student representatives from within the University. Interviewees were identified by the University campus and facilities service project manager are key people who had been, or continue to be, involved in the design and development of both buildings.

Interview questions focused on what worked well during the project, what the challenges were, and what they thought the lessons for future projects were. Interviews were audio recorded and transcribed where possible. Care was taken to reduce interviewer bias as much as possible through various techniques such as reframing the questions in different ways to ensure triangulation of responses.

Results and Discussion

This section presents the results and discussion from the evaluation of the two study buildings. The technical performance of the building and BUS survey are presented first. This is followed by outcomes from the interviews with a focus on the role of management in achieving triple bottom line (TBL) sustainability outcomes.

Building Performance

For the environmental element of the triple bottom line (TBL) approach, both buildings achieved a Green Star Education certification rating of 5 stars (v1). As evidenced from the interview analysis, this was a standard driven by senior management of the University and integrated into the development from building conception. To achieve a 5 star rating, a benchmark university building should have 44kWh/m^2 annual energy intensity, and 68kWh/m^2 (in terms of electricity and gas) of usable floor area. Energy intensity in this research was measured in terms of electricity and gas usage per building. Electricity was used for lighting and gas was used for heating and cooling. For Building A, energy intensity equates to a total of 104kWh/m^2/year and 57.8kWh/m^2/year (electricity and gas). For Building B, this equates to a total of 82.6kWh/m^2/year and 49.7kWh/m^2/year (electricity and gas). Building A has a higher energy intensity as it is almost double the volume and floor area of Building B (see Table 1).

Table 2 Green Star Educational Design (v1), 5 Star performance energy criteria for study buildings

	Teaching/ Classroom Spaces	Office/ Administrative Spaces	Common Spaces
Total Electricity kWh/m^2/year	68.6	69.5	39.3
Total Gas kWh/m^2/year	14.3	1.5	0.8

Table 3 5 Star performance energy criteria for study buildings

Energy Criteria	Building A Teaching/ Classroom Spaces	Building A Office/ Administrative Spaces	Building A Common Spaces	Building B Teaching/ Classroom Spaces	Building B Office/ Administrative Spaces	Building B Common Spaces
Total Electricity kWh/m²/year	88.2	89.1	49.7	71.5	76.3	41.2
Total Gas kWh/m²/year	23.8	3.2	1.9	17.4	2.1	1.2

Analysis of the utility consumption data found that the energy usage for both buildings was higher, with Building A having a higher value than Building B. Energy use for the administrative spaces in both buildings were higher than the teaching and common spaces, which is logical as they are used mostly throughout the year. On average, the administrative spaces are typically used for 52 weeks of the year and sometimes on weekends for activities such as Open Day etc.

In Building A, energy use in the administrative spaces was 30.2% higher than the common spaces. Again this can be attributed to the fact that common spaces are only used during semesters and in between classes. In Building B, energy use was 5.1% higher. What is significant, however, is that usage is approximately half when compared to University campus buildings (Figure 1). In part, these results are affected by a significantly higher occupancy rate in Building A than in Building B, as well as the fact that Building A is a much bigger building than Building B. In analyzing kWh/m²/occupant based upon actual occupation, the utility consumption for Building A and Building B were found to be 98% and 92% lower than comparable buildings in the university. From a GHG emissions perspective, Building A is performing at 3.5 times and Building B at 1.8 times higher than the predicted rate. The higher value Building A is again in part due to the higher utilization of this building.

The BUS survey confirmed occupant satisfaction with the building in terms of performance and function. The survey found that the building performed excellently in three categories: overall comfort, design and image to visitors. However, it performed poorly in two categories: perceived health and overall noise level. The survey results placed Building A in terms of satisfaction levels in the 64% top percentile, and Building B in the 57% top percentile, compared to Australian benchmark data. This indicated that achieving improved environmental sustainability performance did not compromise occupant satisfaction.

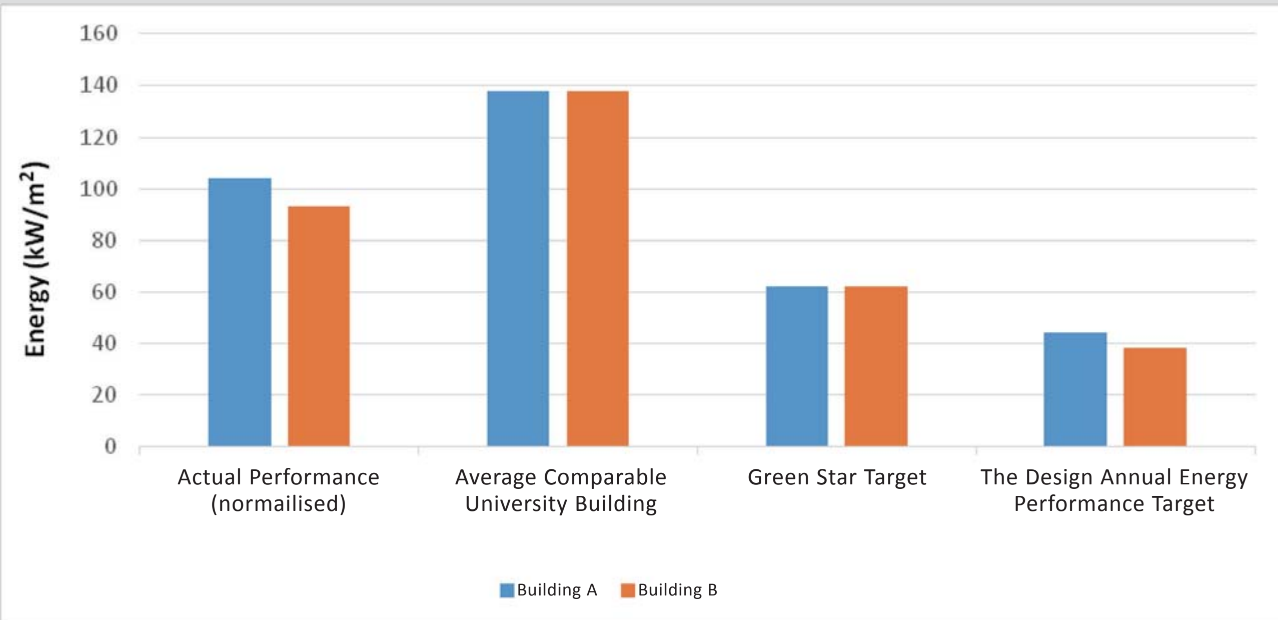


Figure 1 Comparison of actual and target/predicted energy performance

Table 4 BUS survey results for common variables between both case study buildings

Summary Chart 12 key variables.
Each measured on a 7 point slider scale:
1 = unsatisfactory/uncomfortable/poor/less healthy
7 = satisfactory/comfortable/good/more healthy

Color indicated perceived performance against the benchmark data set. There are 3 ratings:

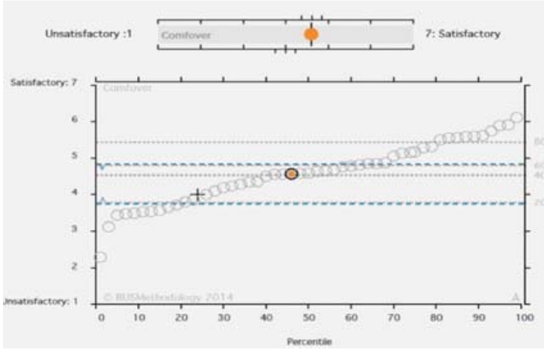
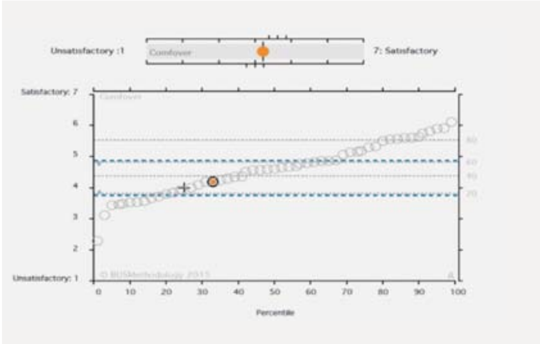
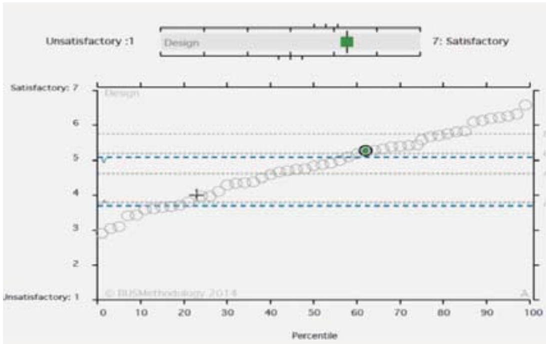
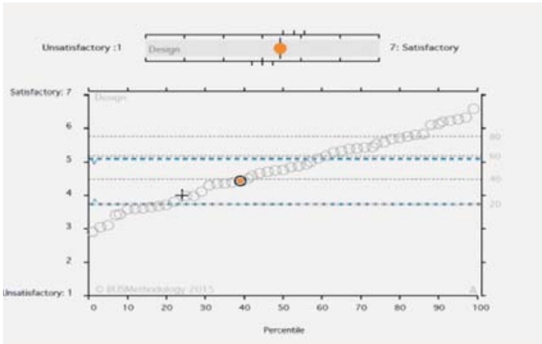
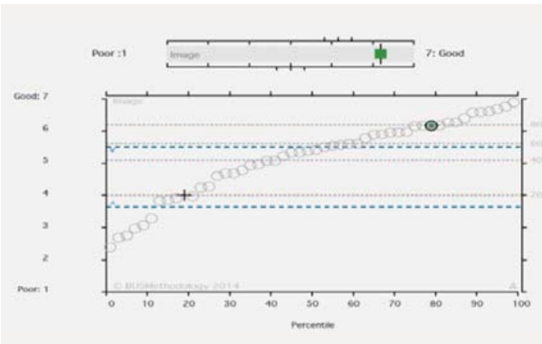
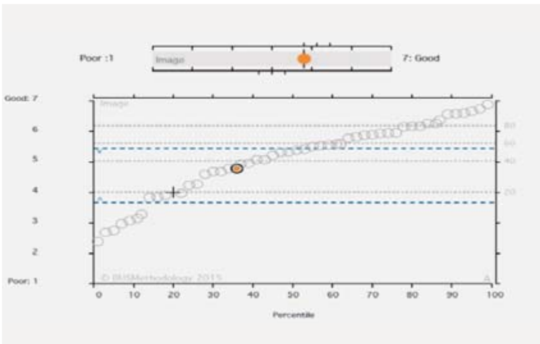
Green	building performing better than data set
Amber	building is average
Red	building under-performing, needs improvement

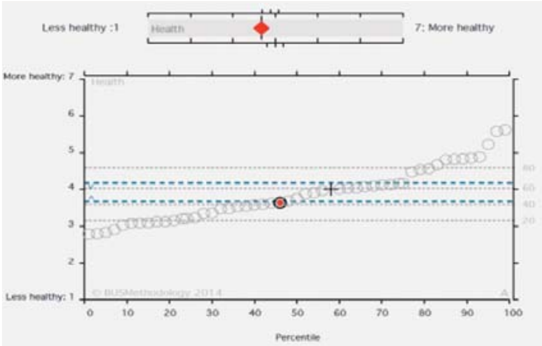
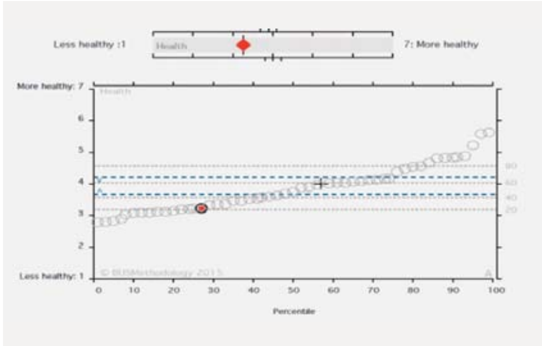
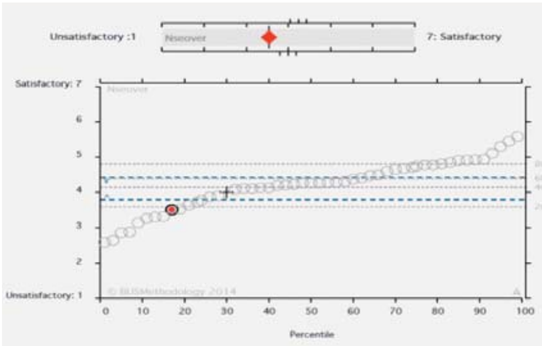
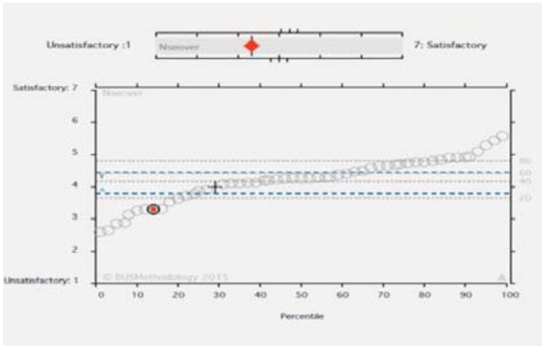
The **graph** shows building performance benchmarked against other Australian buildings. It allows identification of how each variable performs within the building against the benchmark. Dataset available on a percentile chart (0-100), allowing quick identification of 'above' or 'below' average characteristics. It also allows building performance to be rated against the benchmark dataset.

The **circles** (empty fill) are the values of other buildings (commercial only) in the benchmark dataset. **Fill Color** shows test results with the color being green, amber or red (performance against dataset). The two blue **broken lines** represent the upper and lower critical region limits to demonstrate where:

The study building falls, e.g. falls between the critical region limits/falls above the limits.
The **x-axis** represents the percentile score (0-100).
The **y-axis (left)** represents the variable scale (1-7); the **y-axis (right)** quintiles (sample/population is divided into fifths).

+sign represents the scale midpoint: mean of the dataset (in percentile).

Variable	Building A	Building B
Variables that 'Worked Well'		
Overall Comfort		
Building Design		
Image to Visitors		

Variable	Building A	Building B
Variables that 'Did Not Work Well'		
Perceived Health		
Overall Noise		

Interviews

The interviews with key stakeholders found a number of challenges, successes and lesson learned. A summary of key outcomes are presented below, with a focus on the role of management in ensuring TBL sustainability outcomes.

By including the requirement for environmental performance targets in the design brief, the architect and other key stakeholders were able to integrate sustainability outcomes as part of the concept design and discussions from the beginning. This meant that environmental considerations were not added on, but informed the philosophy of the design. The use of the Green Star Educational Design v1 framework meant that a broader consideration of all elements of sustainability was required, rather than just whatever were the key strengths of the stakeholders involved. Both buildings had different policy guidelines; Building A was a fixed price guaranteed contract while Building B was a traditional design and build (designed and build by different entities), hence there is no shared ownership of building performance in the latter compared to the former. The University's facilities and campus services have learnt from this experience and are in the process of integrating a number of outcomes regarding different design into the revision of the various types of University Design and Policy Guidelines.

Overall, the development of both the study buildings has been very successful from an environmental sustainability perspective, occupant perspective and financial perspective. However there are lessons which can be drawn upon for future developments to improve outcomes further.

Conclusion

The study presented an analysis of the gap between actual and expected performance in two University Green Star buildings. It demonstrated how POE generated results assisted to achieve this objective. Outcomes included the development of clear assessment mechanisms for establishing the link between building performance measurement and performance management with an understanding of how occupants viewed its value. In addition, the buildings were compared to other University buildings to understand if the energy performance of the building did achieve expectations. Comparisons were carried out on how well the buildings have been managed post construction (in conjunction with annual energy targets), improved (where required) and reported.

From the analysis of POE results of the case study buildings, it clearly indicated that building users (academic and non-academic staff) were dissatisfied in all categories of the BUS survey such as noise and perceived health, and their needs had not been considered in the design brief and throughout the progress of the project. However, after triangulating the outcomes and examining the broader context, both buildings met their key parameters in terms of Green Star certification and energy performance. Most of the factors related to the design, overall performance and study spaces worked well with the exception of a few concerns about temperature fluctuations, noise and storage issues according to the users.

In both buildings, the decision to create Green Star standard buildings was entirely management driven. The buildings were created mainly from a teaching and learning perspective and to achieve high rates of student satisfaction. Focusing on the true building users (academic and non academic staff, as opposed to students who are a transient population) was not one of the key agendas in the framework and design intent, leaving building users dissatisfied. This major gap is found in theory as well as practical emerging examples worldwide where building user interests are not being considered in the design and development of the building. This lack of consultation leads to lower productivity and ineffective performance management of buildings in the long run. Dissatisfied users also prove that respective built environment management frameworks are not well structured, lacking appropriate stakeholder management and understanding of their potential impact on project success. Hence the study indicated that focusing on technical issues alone to achieve building sustainability is not sufficient for a building's success. Being "green" is only one important feature of building success, but other aspects of the building (for example, user needs and comfort) must be considered as well.

POE can provide insights which ultimately can contribute to the continual improvement of a building provided it is well executed. The POE outcomes in this study reflected the value people and processes play in designing, building, using and operating/maintaining buildings. Ultimately, this may be seen as a process to promote and capture valuable data which demonstrates measurable return on investments, creates dialogue between individuals and teams from multidisciplinary service delivery streams, as well as engaging with end users. Based on the results, this paper emphasizes the integration of POE services as a streamlining activity that needs to be incorporated as part of the management framework for new as well as existing building stock.

The research outcomes of the study can be applied to other areas of owner occupied assets such as private property managers as well as government. While this study did not specifically look at productivity in green buildings, this is another area that can be added on to obtain a holistic picture of design, performance and user engagement to optimize outcomes.

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