2016

# Modelling and performance evaluation of net zero energy buildings

Joel Anderson
*University of Wollongong*

# MODELLING AND PERFORMANCE EVALUATION OF NET ZERO ENERGY BUILDINGS

A thesis submitted in fulfilment of the requirements for the award of the degree

**Master of Philosophy**

**from**

**UNIVERSITY OF WOLLONGONG**

By

Joel Anderson, B.E (Mechanical) (Hons)

School of Electrical, Computer, and Telecommunications Engineering

2016

# Declaration

I, Joel Anderson, declare that this thesis, submitted in fulfilment of the requirements for the award of Master of Philosophy, in the School of Electrical, Computer, and Telecommunications Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Joel Anderson

# Abstract

Developing a design philosophy to reduce carbon emissions from the built environment is a major motivator for the formation of the net zero energy concept. For net zero energy buildings to be widely adopted, a deeper understanding of the drivers of their success is needed, as well as their comparative differences and similarities to buildings of more conventional design. This thesis investigates the effects of different building design and operation principles in relation to net zero energy buildings. Simulations of three case study buildings (two of which are designed to be net zero energy) were performed to identify the building design and operation elements which contribute most to energy efficiency.

Through development and validation of building models of both net zero and conventional designs in this thesis, it was found that validation of smaller, more energy efficient building models can present challenges less commonly encountered in models of more conventional buildings. An understanding of the sensitivities of net zero energy buildings to alterations in design and specification were gained. Results show that net zero energy buildings are more sensitive to changes such as glazing type, and HVAC setpoint based on the case studies presented.

This thesis has looked at quantifying the contribution of different building elements and systems to overall energy savings via simulation. The net impact of different glazing types, lighting control methods, window shading schedules, and HVAC set points on overall building energy consumption were examined.

This thesis also reports on the net zero energy balance for one case study building. Results show that the building was net positive for the 12-month period considered. Both energy imported/exported and energy generated/consumed were considered, as well as the load matching, grid interaction, and some preliminary analysis of power quality factors. These power quality factors and their relationship with net zero energy buildings must be understood before the net zero concept can be widely adopted.

# Acknowledgements

This research has been conducted with the support of the Australian Government Research Training Program Scholarship.

# Contents

# List of tables

# List of figures

# List of abbreviations

| | |
|---|---|
| AHU | Air Handling Unit |
| ASHP | Air Source Heat Pump |
| BASIX | Building Sustainability Index |
| BIPVT | Building-Integrated Photovoltaic Thermal |
| BMS | Building Management System |
| CASBEE | Comprehensive Assessment System for Built Environment Efficiency |
| COP | Coefficient of Performance |
| CVRMSE | Coefficient of Variation of Root Mean Squared Error |
| DG | Distributed Generation |
| DHW | Domestic Hot Water |
| DSM | Demand Side Management |
| E1 | Enterprise 1 |
| EE | Energy Efficiency |
| EPBT | Embodied Energy Payback Time |
| EUB | Energy Use Breakdown |
| GBCA | Green Building Council of Australia |
| GHG | Green House Gas |
| GII | Grid Interaction Index |
| GPO | General Purpose Outlet |
| GSHP | Ground Source Heat Pump |
| HVAC | Heating Ventilation and Air Conditioning |
| IEA | International Energy Agency |
| IEQ | Indoor Environmental Quality |
| LBC | Living Building Challenge |
| LEED | Leadership in Energy and Environmental Design |
| LM | Load Matching |
| LMI | Load-Match Index |
| LowE | Low Emissivity |
| LPD | Lighting Power Density |
| lx | Lux |
| NABERS | National Australian Built Environment Rating Scheme |

| | |
|---|---|
| NMBE | Normalised Mean Bias Error |
| NZE | Net Zero Energy |
| NZEB | Net Zero Energy Building |
| PEF | Primary Energy Factor |
| PIR | Photo Infrared |
| PQ | Power Quality |
| PQA | Power Quality Analyser |
| PV | Photovoltaic |
| REC | Renewable Energy Certificate/Credit |
| SBRC | Sustainable Buildings Research Centre |
| SHGC | Solar Heat Gain Coefficient |
| TAFE | Technical And Further Education |
| THD | Total Harmonic Distortion |
| THDI | Total Harmonic Distortion – Current |
| THDV | Total Harmonic Distortion – Voltage |
| TMY | Typical Meteorological Year |
| TTT | Transformational Technical Training building |
| UOW | University Of Wollongong |
| VAV | Variable Air Volume |
| VDI | Virtual Desktop Infrastructure |
| WFR | Window to Floor area Ratio |
| WWR | Window to Wall area Ratio |

# Chapter 1 Introduction

## 1.1 Statement of the problem

With increasing average temperatures and more frequent extreme weather events as a result of anthropogenic climate change, there is increased pressure on maintaining a comfortable environment for building occupants while minimising building energy use. In a study of the relationship between climate change, indoor thermal environment, and building energy use, it was found that based on 2070 global warming predictions, building energy use could be expected to rise by a range between 0.4% and 15.1% depending on future climate scenarios and building location and design [1]. The studies on Australian buildings predicted that temperate climates such as Sydney are likely to be most sensitive to climate change, with cooling loads of buildings increasing by up to 101% [2].

The development of a new energy neutral, comfortable building design philosophy is necessary to mitigate – and adapt to – the effects of climate change. Net zero energy buildings are a way of meeting this new challenge.

Meeting the Net Zero Energy (NZE) requirements in Australian buildings is an opportune area of research, with the goal of achieving net zero energy consumption becoming more achievable due to the ongoing development of small scale solar and wind technologies, and the emerging development of off-grid energy storage.

## 1.2 Research aim and objectives

The aim of this research is to evaluate the impact of existing building designs, components, and operational parameters on fulfilling net zero energy requirements of the University of Wollongong's (UOW) Sustainable Buildings Research Centre (SBRC) facility and Technical and Further Education TAFE Illawarra's Transformational Technical Training (TTT) building as part of the Living Building Challenge [3]. The overall aim of the project is to address the following objectives:

1. Conducting a comprehensive literature review of current and past studies on the building sustainability and net zero energy fields;
2. Development of building simulation models of the case study buildings using DesignBuilder building performance simulation software for evaluating the

impact of building design, components and operational parameters on the overall building energy use;

3. Validation of building models using real data collected from the case study buildings;
4. Perform building simulations to evaluate the effectiveness of various designs and operation strategies for each case study building and identify the most effective ways of achieving net zero energy in a building;
5. Collect electricity consumption and generation data from case study buildings and report on its progress in achieving net zero energy over its lifetime;
6. Report on load match and grid interaction factors, as well as basic power quality considerations in net zero energy buildings through a case study building.

In addition to the two energy efficient case study buildings of the SBRC facility and TTT building, an additional modern commercial building was also selected for comparison against the net zero test cases.

## 1.3 Research methodology

In order to improve understanding of building operation and energy use, simulation models of the case study buildings were developed in DesignBuilder. The 3D geometry of each building comes from the as-built architectural drawings, while HVAC and lighting specifications are sourced from the operation manual, as well as mechanical and electrical drawings of the buildings.

Validation of the building models was carried out to ensure the models are appropriately representative of the real buildings. To do this, historical weather data sourced from the Bureau of Meteorology and the buildings' own weather stations was coupled with historical energy consumption and temperature data sourced from each building. By performing benchmark simulations with the real weather data, the behaviour of the simulated building was able to be compared to that of the real building with a common weather input.

Once the benchmark model had been validated using historical weather data, it was then modified according to different scenarios in order to determine the contribution of each energy-saving technology to the overall performance of the building. The intended outcome of these experiments was to understand some of the contributing factors to energy efficiency in buildings.

The real weather data used for validation was sometimes not complete and/or not always appropriate for the simulations. Accordingly, Typical Meteorological Year (TMY) weather data was used. The reason for this is that TMY data is an amalgamation of many years of weather data from the particular location in question, averaged out into a year of representative data. This eliminates any extreme weather events and unseasonable weather which may bias simulation results.

The collection of consumption and generation data for the test cases was mainly sourced via the Building Management Systems (BMS) of the respective buildings'. The SBRC BMS has a comprehensive data trending ability and electrical metering is available down to a high level of detail for both loads and generators.

## 1.4 Publications related to this thesis

- J. Anderson, D. A. Robinson, and Z. Ma, "Energy Analysis of Net Zero Energy Buildings: A Case Study," in 12th REHVA World Congress CLIMA 2016, 2016.

  *Accepted for publication, and presented in May, 2016.*

## 1.5 Thesis structure

The current chapter outlines the aims and objectives of this thesis. It presents the key research methodologies employed. The subsequent chapters are organised as follows:

- Chapter 2 presents a comprehensive review of the literature relating to net zero energy buildings;

- Chapter 3 gives a description of the buildings used as case studies in this thesis as well as the building simulation and model validation methodologies.

- Chapter 4 provides background of the development of each case study building model and the planned outcomes of the simulations. The validation process of each model is documented including quantification of associated errors.

- Chapter 5 presents the results of the building simulations on each test case and discusses the results and their implications for NZEBs.

- Chapter 6 is a presentation of the energy balance of a case study building based on measured energy consumption and generation data. An analysis of the load matching and grid interaction factors of the case study building, as well as some power quality factors and implications of these for the utility grid is carried out.

- Chapter 7 details the conclusions that can be drawn from research presented in this thesis and outlines the potential for future work in this field.

# Chapter 2 Literature Review

## 2.1 Background

The exponential growth, both in terms of economy and population throughout the world, especially in developing countries, has resulted in dramatic increases in global primary energy consumption. The demand for energy in recent decades has been met overwhelmingly by fossil fuel resources. A side-effect of this is the onset of significant climate change that will affect life on planet Earth for all living species.

For the human race, significant climate change means that urgent changes need to be made to the way we live, and where we live, with increased pressures on our built environment coming over time from a warming climate and more extreme weather events. These changes give rise to the need for us to change the way our built environment works; our building designs and codes, our energy consumption, how we source our energy, as well as our own personal behaviour and living habits.

A focus on energy efficiency in our buildings is needed. Building performance certification schemes are promising ways of ensuring buildings deliver meaningful energy reduction in a structured and certified way. To enable effective implementation of these performance targets, consistent methodologies need to be developed to ensure reliable verification is able to take place. In addition to energy efficiency measures, it is important that buildings are able to offset the reduced amount of energy that they consume. On-site renewable generation is the best way of achieving this through rooftop solar in most cases, though other methods such as the purchase of Renewable Energy Certificates (REC) are also feasible for buildings where on-site renewable generation is not possible.

### 2.1.1 The growth of global energy consumption

In their review of the sustainable development implications of zero energy buildings, Li et al. [4] noted that during the rapid growth of the Chinese economy over the past few decades, primary energy consumption increased from 0.57 billion tonnes of oil-equivalent in 1978 to 3.25 billion tonnes in 2010 – growth of 470% and overtaking the US as the world's largest energy producer in 2009.

Through review of building energy consumption information, Pérez-Lombard et al. [5] observed that global primary energy consumption grew by 49% between 1984 and

2004, attributing this to the rapid growth of developing economies and their resulting improved living conditions. They concluded that current energy and socio-economic systems are unsustainable.

Global energy demand is predicted to continue its growth trajectory onwards to 2035 according the International Energy Agency (IEA) in their World Energy Outlook report for 2013 [6]. The report noted however that government policies during this time will likely have significant impact on the consumption trend. The IEA's '*new policies*' scenario forecasted that all sources of energy will continue to grow during the period to 2035, but that renewable energy will grow by the greatest margin of 77% worldwide. The consequence of this increased energy demand is that $CO_2$ emissions are predicted to increase by 20%.

### 2.1.2 Impacts of climate change on the built environment

With increased average temperatures as a result of anthropogenic climate change, there is an increased pressure on our buildings to maintain a comfortable environment for occupants. In a study of the relationship among climate change, the indoor thermal environment and building energy use, Guan [1] found that building energy use could be expected to rise by 0.4-15.1% depending on future climate scenarios and building location and design, based on global warming predictions to the year 2070. Various adaptation strategies were examined and it was suggested that the required heating and cooling loads, and ultimately the overall energy use, could be reduced if the internal load density of the building was reduced. These internal loads were defined as those loads which generate heat and come from within the building envelope (e.g lighting and plug loads). Further research into a ranking system of the viability of different mitigation and adaptation strategies was suggested to enable optimising retrofit and design projects.

A similar study into the relationship between buildings and climate change was performed by de Wilde and Coley [7]. The authors warned that existing rules and regulations in the building sector are based on historical climate data and are therefore not necessarily well suited to the future in a warmer climate. They also suggested that existing performance metrics should be considered carefully to account for human perception of thermal comfort and their adaptation to wider temperature bands. Performance metrics are methods by which the success and performance of a building is measured over a variety of categories such as energy consumption or thermal comfort surveys.

The potential impact of climate change on the energy requirements associated with heating and cooling in five residential buildings throughout Australia was examined by Wang et al. [2]. A major finding was that a significant impact on the heating and cooling energy requirements may occur within the lifetime of the existing building stock – highlighting that more research is required on retrofitting to mitigate these potential impacts. Depending on the climate zone in which the building is situated, it was predicted that by 2050, the total heating/cooling requirements of a newly constructed 5-star house (NABERS rating) would vary within the range of -26% (where the warming climate would reduce the heating load of a building in a location with a traditionally high heating requirement) to 101% for more cooling dominated climates. Temperate climates such as Sydney, where heating and cooling loads are relatively balanced, are likely to be most sensitive to climate change, although Wang et al. [2] noted that further studies are needed to investigate the implications of different types and sizes of buildings. In addition, the thermostat settings used in this analysis were those specified in current Australian building codes and did not consider the future alterations of these codes, or future occupant behavioural adaptation.

Simulations were performed by Ren et al. [8] on existing and new residential buildings in eight varying climate zones throughout Australia and identified potential adaptation pathways to mitigate the effects of climate change and maintain current cooling/heating energy requirements. It was concluded that a good level of adaptive capacity was possible through energy efficiency measures for heating dominated buildings. For cooling dominated buildings, additional measures are needed such as renewable energy to offset the energy required by the larger cooling load.

Climate change's impact on the built environment will manifest itself through increased energy use due to the increased HVAC capacity required to cope with a warming outside climate. It is clear that building codes must be updated to address the future impacts on the built environment from climate change. The introduction of energy efficiency measures and renewable energy resources make it possible for buildings to adapt to these changes, maintaining a comfortable environment for occupants, whilst dramatically reducing the energy required.

### 2.1.3 The need for net zero energy buildings

To mitigate the impact of climate change on the built environment, it is necessary to develop a new design philosophy for our buildings that enable occupants to remain comfortable in a warming climate, as well as reduce the environmental footprint and emissions intensity of our structures.

Wilkinson et al. [9] argued that by decarbonising the built environment through strategic changes to the way we use building elements such as insulation, ventilation, fuel switching, and behavioural change, there is potential to prevent 5500 premature indoor environment related deaths every year, as well as save 41 Mt of $CO_2$ emissions.

Whilst there may be many benefits to rethinking how we design our built environment, Pérez-Lombard et al. [5] suggested that it will be business as usual despite an increased emphasis on energy efficiency minimum requirements, unless regulation steps in to both raise social awareness of sustainability issues, and to enable new technologies for energy production and energy conservation to enter the market.

In a review of the current status and future potential of the building sector in the UK, Clarke et al. [10] highlighted the fact that many buildings have very poor energy performance due to being constructed before building energy standards were developed. This, combined with increases in electrical energy use, leads to the potential for significant improvements in the efficiency of current building stock. The need for upskilling in the industry to cope with new building technologies is identified by the authors.

The proliferation of low energy intensive buildings which meet their own energy needs through renewable means has great potential to minimise the effects of climate change, and provide many public health benefits as a result. Whilst some regulation and industry training incentives may be required to encourage the take-up of such changes, there is huge potential in retrofitting existing building stock to minimise and perhaps eliminate their net energy use.

## 2.2 Net zero energy building definitions

In principle, the concept of a Net zero Energy Building (NZEB) is relatively simple – a building that produces at least as much energy as it consumes. However there are many potential ways to define the ‘zero’ balance. Depending on the objective of the building in question, and the regulatory environment in its jurisdiction, the specific definition of ‘net zero’ may vary.

Torcellini & Pless [11] studied four of the more common definitions in the literature and discussed their applications, advantages, and disadvantages. They stated that a good NZEB definition must first prioritise energy efficiency over renewable energy capacity. A reduced load will lead to reduced required installed capacity of renewable energy, leading to significant cost savings and making the NZEB goal more achievable.

The definitions studied in Torcellini & Pless [11] use the utility grid as a means of accounting for net use. The four definitions discussed are net-zero site, net-zero source, net-zero costs, and net-zero emissions:

- Net zero site – a NZEB that produces at least as much energy *on site*, as it consumes in a year, accounted for at the site;
- Net zero source – a NZEB that produces at least as much energy as it uses in a year, accounted for at the source. Source energy considers the primary energy used to generate and transport the energy to the site. This is important when accounting for energy consumed from the grid, where a significant portion of energy is lost during transmission from generator to site, and in thermal generation efficiency losses;
- Net zero cost – this balances the costs rather than the units of energy. So the amount of money paid to the building owners/tenants by the utility for the energy it exports, is at least equal to the amount spent by the building owners/tenants for energy imported from the grid;
- Net zero emissions – again, a different metric is used to define the balance: this time, emissions. The building produces at least as much emission-free energy to offset the emissions intensive energy imported from the grid. Here, non-energy differences between fuels such as carbon emissions, and other types of pollution are accounted for. This makes it a more comprehensive definition than the others but as a result, it is more difficult to implement.

The authors argued that the definition influences the design of the building and vice versa. Depending on the definition, the emphasis can be placed on energy efficiency, energy supply strategies, or a number of other factors which in turn influence practical aspects of the building's design and operation. Table 2-1 summarises the advantages and disadvantages of the four definitions discussed.

Table 2-1 NZEB definitions and advantages/disadvantages from [11].

| Defini-tion | Pluses | Minuses | Other Issues |
|---|---|---|---|
| **Site ZEB** | • Easy to implement.<br>• Verifiable through on-site measurements.<br>• Conservative approach to achieving ZEB.<br>• No externalities affect performance, can track success over time.<br>• Easy for the building community to understand and communicate.<br>• Encourages energy-efficient building designs. | • Requires more PV export to offset natural gas.<br>• Does not consider all utility costs (can have a low load factor).<br>• Not able to equate fuel types.<br>• Does not account for nonenergy differences between fuel types (supply availability, pollution). | |
| **Source ZEB** | • Able to equate energy value of fuel types used at the site.<br>• Better model for impact on national energy system.<br>• Easier ZEB to reach. | • Does not account for nonenergy differences between fuel types (supply availability, pollution).<br>• Source calculations too broad (do not account for regional or daily variations in electricity generation heat rates).<br>• Source energy use accounting and fuel switching can have a larger impact than efficiency technologies.<br>• Does not consider all energy costs (can have a low load factor). | • Need to develop site-to-source conversion factors, which require significant amounts of information to define. |
| **Cost ZEB** | • Easy to implement and measure.<br>• Market forces result in a good balance between fuel types.<br>• Allows for demand-responsive control.<br>• Verifiable from utility bills. | • May not reflect impact to national grid for demand, as extra PV generation can be more valuable for reducing demand with on-site storage than exporting to the grid.<br>• Requires net-metering agreements such that exported electricity can offset energy and nonenergy charges.<br>• Highly volatile energy rates make for difficult tracking over time. | • Offsetting monthly service and infrastructure charges require going beyond ZEB.<br>• Net metering is not well established, often with capacity limits and at buyback rates lower than retail rates. |
| **Emis-sions ZEB** | • Better model for green power.<br>• Accounts for nonenergy differences between fuel types (pollution, greenhouse gases).<br>• Easier ZEB to reach. | | • Need appropriate emission factors. |

In a similar fashion to Torcellini & Pless [11], the understanding of a lack of consistent international definition of NZEB was addressed by Sartori et al. [12]. It was recognised that different definitions were possible to describe NZEBs depending on their purpose and regulatory targets. A framework by which to set definitions was proposed according to 5 criteria as described below and a methodology around this was developed to enable setting of NZEB definitions in a systematic way. The NZEB framework criteria is a refined version of Sartori et al. [13] and is organised as follows:

1. Building system boundary – energy flows that cross the defined system boundary are considered in the NZEB analysis. Those energy flows that don't, are disregarded;

2. Weighting System – the weighting of different energy sources allows the comparison of different sources throughout the energy chain on a normalised basis. This allows for comparison of factors such as site and source energy, and fuel switching (e.g. PV generation in summer, biomass generators in winter), as well as cost and emissions metrics where there are differences between energy sources in terms of generation and transmission costs, and emissions per unit of energy supplied;
3. NZEB Balance – a number of factors influence the outcome of the NZEB balance such as the time period over which the balance is calculated, the type of balance, and whether there are minimum energy efficiency requirements that must be met before NZEB status can be achieved. The balance period is typically taken to be a year, as this will account for seasonal cycles. A building that may not produce enough energy in winter may still generate a large surplus in summer from its PV system and as such compensates for the winter deficit. Some argue that a longer period closer to the building's total lifespan should be taken to account for the embodied energy of the building. However it is possible to annualise the contribution of the embodied energy so that this can still be considered using an annual balance period. The type of balance has a significant influence on the achievability of the NZEB goal;
4. Temporal Energy Match Characteristics – in addition to a NZEB being able to achieve balance over the balance period, there are other factors to be addressed concerning the building's interaction with the grid, as well as its potential to produce enough energy at times of peak consumption;
5. Measurement and Verification – in order to check that the building is complying with NZEB requirements, the authors argue that a proper measurement and verification process be put in place. This process would be dependent on the rest of the criteria discussed previously. It is argued that a measurement and verification process should at least keep track of the energy import/export balance, but it is recommended that further detail such as temporal load characteristics be considered, as well as occupant comfort.

Two key challenges have been identified by Marszal et al. [14] that require attention before the proper integration of NZEBs into national and international building codes can occur. These include the need to adapt a common and unambiguous definition, and to determine a standard methodology for calculating the energy balance. The metric of the energy balance is recognised as being the most important point to address. The authors state that while the delivered energy metric is the most easy to implement, it does not account for primary energy losses and different types of energy. As such, the primary energy metric is recommended.

A classification system based around the type of renewable energy resource use was created by Pless & Torcellini [15]. The system ranges from NZEB:A to NZEB:D as shown in Table 2-2. NZEB:A is a building that offsets all of its energy use from the renewable energy available within the building footprint, whilst NZEB:D is a building that achieves balance through a combination of on-site renewable energy and the purchasing of renewable energy credits from an outside source. The aim of this classification system is to encourage designers to first implement significant energy efficiency measures before sizing an appropriate renewable energy system in order to keep required capacity down as much as possible.

Table 2-2 NZEB classification by [15].

| NZEB Classification | Supply Option Number | NZEB Supply-Side Options | NZEB Definitions Met |
|---|---|---|---|
| | 0 | Reduce site energy use through energy efficiency and demand-side renewable building technologies. | NA |
| | **On-Site Supply Options** | | |
| A | 1 | Use RE sources available within the building's footprint and connected to the building's electricity or hot/chilled water distribution system.<br>Reach an NZEB position without needing NZEB:B, NZEB:C, or NZEB:D sources. | YES: Site, Source, Emissions<br>Difficult: Cost<br>Potential Issues:<br>• Reaching a source or emissions NZEB position is difficult if multipliers are high when utility energy is used but low when exporting to the grid.<br>• Qualifying as a cost NZEB may be difficult if net metering policies are unfavorable. |
| B | 2 | NZEB:A sources may also be used<br>and<br>Use RE sources that are outside the building footprint but still within the building site and connected to the building's electricity or hot/chilled water distribution system.<br>Reach an NZEB position without needing NZEB:C or NZEB:D sources. | YES: Site, Source, Cost, Emissions<br>Difficult: Cost<br>Potential Issues:<br>• Reaching a source or emissions NZEB position is difficult if multipliers are high when utility energy is used but low when exporting to the grid.<br>• Qualifying as a cost NZEB may be difficult if net metering policies are unfavorable. |
| | **Off-Site Supply Options** | | |
| C | 3 | NZEB:A and/or NZEB:B sources are used (to the extent feasible)<br>and<br>Use RE sources available off-site to generate energy through on-site processes connected to the building's electricity or hot/chilled water distribution system.<br>Reach an NZEB position without needing NZEB:D sources. | YES: Site<br>Difficult: Source, Cost, Emissions<br>Potential Issues:<br>• Reaching a source or emissions NZEB position is difficult if carbon-neutral renewables are used or if source and carbon multipliers are high when utility energy is used but low when exporting to the grid.<br>• Qualifying as a cost NZEB is very difficult because of the cost to purchase and continually transport off-site renewable materials to the site. |
| D | 4 | NZEB:A and/or NZEB:B sources are used (to the extent feasible), NZEB:C sources may also be used<br>and<br>Purchase recently added off-site RE sources, as certified from Green-E (2009) or other equivalent REC programs. Continue to purchase the generation from this new resource to maintain NZEB status. | YES: Source, Emissions<br>NO: Site, Cost<br>Potential Issues:<br>• Reaching a source and emissions NZEB position is based on the type and quantity of the purchased RE.<br>• Qualifying as a site and cost NZEB is not possible. |

A summary of findings by Griffith et al. [16] from research conducted at the American National Renewable Energy Laboratory concluded that the net zero site definition was preferred for analysis due to ease of verification and does not require conversion factors. However as discussed previously, this does not provide the most comprehensive account of the overall energy balance of the building.

## 2.3 Useful data and reporting methods

In order to ensure the NZEB goal is achieved and maintained through the life of the building it is important that data is easily obtained and shown through a sound methodology, whether balance is achievable or not. A number of parameters need to be defined depending on the type of NZEB building in question, and suitable reporting methods must also be developed.

In a review of definitions and calculation methodologies by Marszal et al. [14], it is argued that before a consistent definition can be developed, a number of factors need to first be considered:

- The metric of the energy balance
- Balance period
- Type of energy to be included in balance
- Type of energy balance
- Accepted renewable energy supply options
- Grid connection
- Energy efficiency requirements

The study showed that these factors were of particular importance for designers and operators. Possible solutions for the implementation of the above factors were discussed however no recommendations were proposed. Rather, the aim was to give an overall understanding of the various considerations in NZEB design and definition.

### 2.3.1 Balance metric

There are a number of different possible metrics used to define ‘zero’. Marszal et al. [14] considered these metrics and found that the most favoured metric is primary energy because this is quite comprehensive, considering different kinds of energy, as well as the transmission losses from the grid. However the consideration of different kinds of energy becomes complicated due to the underestimation of renewable energy resources. For example, it requires 2-3 units of primary energy to produce 1 unit of delivered energy from coal, while renewable energy sources require 1 unit of primary energy to deliver 1 unit of energy. This means that a suitable conversion factor needs to be adopted. However this factor is not static, as the percentage of renewable energy penetration in the utility grid changes over time.

As well as the primary energy metric, the authors discuss the relevance of using $CO_2$ emissions as the balance metric, given the global focus on emissions reduction. However the point was made that buildings are commonly evaluated on their energy performance as specified by building codes, rather than their emissions performance which would make implementation of this metric difficult.

### 2.3.2 Balance period

The period of balance can have an impact on the achievability of the goal given the seasonal variability of renewable energy resources. Sartori et al. [12] argued that a yearly balance covering all seasonal conditions is most suitable. Longer periods in the order of decades may be selected to account for embodied energy; however it is possible to annualise this contribution to retain a yearly balance period. These findings are generally in keeping with those found by Marszal et al. [14].

### 2.3.3 Type of balance

Marszal et al. [14] argued that for a grid connected NZEB, there are two possible types of balance: energy use/renewable generation, and energy delivered from grid/energy fed into grid. It was stated that energy use/renewable energy generated is more applicable for the design phase of a building while the delivered/exported balance should be used in operational monitoring. Despite this, it was concluded that the most popular balance in the literature at the time was energy use/renewable energy generated. Sartori et al. [12] concurs with the study by Marszal et al. [14].

### 2.3.4 Measurement and verification

To ensure proper compliance with the applied NZEB definition, a comprehensive measurement and verification methodology should be implemented. Sartori et al. [12] argued that as a bare minimum, this methodology should assess the energy import/export balance, but that it would be beneficial to go further and assess the temporal load match and grid interaction characteristics, as well as occupant comfort and Indoor Environmental Quality (IEQ).

A Microsoft Excel based tool was developed by Belleri et al. [17] which assessed the balance, operating costs, and load match index for NZEBs base on a set of pre-defined definitions. It is suitable for designers, managers and policy makers in gauging the potential success of an NZEB, as well as monitoring the building during operation.

The pre-defined definitions are decided by the tool through user input of a number of parameters. The monthly or yearly energy supply/demand is able to be entered, and desired weighting factors specified. The analysis period can be either yearly or monthly and a number of different metrics are able to be chosen. The authors performed a case study on a planned office building in Italy. The use of the tool enabled designers to assess the predicted success of the building according to different definitions of NZEB.

A standardised monitoring and verification procedure was developed by Noris et al. [18] to assist in planning, installation, and operation. They noted that several common strategies already exist:

- Whole building approach – measures energy flow to/from entire building;
- Sub-metering approach – measurements of isolated energy uses are carried out;
- Indoor comfort – comfort parameters are measured to assess occupant comfort and identify any system malfunctions.

The steps to be considered in the three phases of NZEB monitoring as proposed by Noris et al [18] are summarised below:

*Planning:*

- Set monitoring objective and goals – determine any desired indices such as load match and heating demand as well as IEQ;
- Collect building data – consider the energy flow present throughout the building according to a standard format;
- Identify monitoring boundaries – these boundaries depend very much on the definition being used and it is important that these are identified early and are consistent with the definition chosen;
- Select metrics – different levels of monitoring may be considered based on the monitoring goals chosen. It is stated that the minimum requirement is to obtain the data required for balance verification. But further information regarding IEQ and the delivered/exported balance would be beneficial;
- Perform data reduction – if possible, dependent metrics should be evaluated according to their relationships to independent metrics. This ensures the size of the data required is diminished, saving monitoring costs. This strategy can

reduce data reliability so close attention should be paid to the implications of this strategy specific to each case;

- Define data collection frequency and duration – this factor depends highly on the balance period selected in most cases. Monthly data is adequate for most cases such as energy balance, however higher resolution data in the order of hourly or sub-hourly is beneficial for the monitoring of load match and grid interaction characteristics;
- Identify suitable sensors and data acquisition – with the necessary metrics having been defined and the required data needed to assess them, it is possible now to identify the specific sensors needed to measure the data. Factors such as measurement duration, sample rate and desired accuracy must be considered.

*Installing:*

- Assess technical feasibility – it must be verified whether the selected equipment is able to be installed in the building satisfactorily;
- Recognise and solve metering gaps – proper measures should be identified to overcome any technical issues that result from the technical feasibility assessment. This step must also consider the possible implications for the data quality;
- Final plan and install;
- Commissioning – all components of the monitoring system must be set up to give accurate and reliable service and tested extensively. This is a complex but necessary task.

*Operation:*

- Define data quality assurance procedures – it is necessary to define quality assurance protocols during operation for all data acquired and develop contingencies for when data may be missing due to instrument breakdown, as an example. In this case, an estimation procedure based on historical data may be necessary;
- Post processing – raw data must be processed to calculate the balance and other indicators of building performance. A standard procedure for this step should be developed to ensure consistency through the life of the building;

- Reporting – a report will need to be delivered at the end of each balance period. The authors of [18] recommend that a standard reporting procedure be developed that contains the following three sections:
    - A description of the building and its monitoring system including design data and monitoring system specification. This section remains static and constant throughout all reports in most cases, unless upgrades or modifications are performed
    - The results of the current year with easy to understand standardised diagrams and explanations of the results (climate conditions, occupancy rates etc.)
    - Elaboration on all the data in the second section, and of observed trends throughout previous reports.
- Planning and implementation of operational maintenance – this is needed to ensure the monitoring system works consistently across all balance periods and remains accurate and reliable. Maintenance activities should be planned at appropriate intervals to check instrument calibration and data storage integrity.

A report by Marszal & Bourrelle [19] aimed to understand the differing approaches that currently exist to calculate the energy balance of NZEBs. The importance of variable selection is highlighted and the gap between the suggested methodology and European building codes is examined to highlight the areas that need improvement in building codes to bring them up to the standard of NZEB requirements. The most favoured methodology was found to be the balance between energy use and renewable energy generation. However, the ambiguity of ‘energy use’ shows that further definition is needed to refine what is meant (calculated energy demand or actual measured consumption). As well as this, the type of energy used in the analysis must also be specified.

Measurement and verification tools and methodologies are essential in ensuring energy flows within a building can be accounted for and comprehensively documented in order to ensure NZEB status is attained and maintained. The data required must be identified and obtained through the installation of suitable instrumentation. Depending on the definition of NZEB that is being used, decisions must be made on the type of metric, the period of balance, and types of energy to be included in the balance.

## 2.4 Certification schemes

A number of organisations, both government and non-government, have responded to the increased awareness of building sustainability by developing codes, standards, and rating systems designed around a framework of sustainability factors such as energy use, water use, and building materials. These schemes are designed to assist owners, designers, builders, and managers in developing their buildings according to an established standard. A few of the main certification schemes that are in operation worldwide are discussed below.

### 2.4.1 Description of certification schemes

#### *2.4.1.1 BREEAM*

The Building Research Establishment Environmental Assessment Methodology (BREEAM) has been operating since 1990 and is widely considered to be the world's most popular scheme [20]. BREEAM was developed by the Building Research Establishment (BRE). It enables developers, designers, and building managers to improve the environmental performance of their buildings through a rating system that considers energy and water use, occupant health, pollution, transport implications, building materials, and building waste, as well as the environmental ecology impacts and building management processes [21].

BREEAM claims to be the most widely used scheme in the UK and also operates in several other countries including Germany, The Netherlands, Norway, Spain, Sweden, and Austria. Several variations of the BREEAM scheme exist depending on the regulatory environment of the country in which it operates, as well as the type of building and its use (new or existing construction, community or stand-alone building, residential or commercial)[22].

#### *2.4.1.2 LEED*

Leadership in Energy and Environmental Design (LEED) is a certification scheme developed by the US Green Building Council (USGBC) that considers the design, construction, operation, and maintenance of green buildings. Similar to the BREEAM system, LEED is flexible to different project development and delivery processes by having different rating systems depending on the type of project being considered. LEED's five rating system groups include Building Design and Construction; Interior

Design and Construction; Building Operations and Maintenance; Neighbourhood Development; and Homes [23].

#### *2.4.1.3 NABERS*

The National Australian Built Environment Rating System (NABERS) provides a comparison of the environmental performance of different Australian buildings. The energy efficiency, water use, waste management, IEQ, and environmental impacts are measured and a 'Star' rating is applied to show relative operational performance compared to pre-defined benchmarks [24].

##### *Rating system*

As with the previous certification schemes discussed, the NABERS scheme includes slightly different versions of the tools for the specific project being considered. There are different variations of the tool for offices, hotels, shopping centres, data centres, and homes. Twelve months of measured performance data is used to come up with a star rating from zero to six. The measured performance data includes usage figures for aspects such as electricity, gas, and water. Performance is compared to building benchmarks that represent the performance of nearby buildings of a similar design.

In order to ensure performance data is comparable to the benchmarks, adjustment factors may be used to account for the buildings climatic conditions, occupancy hours, level of amenities, energy sources, and size. The star rating awarded is an indication of its relative performance to the defined benchmark. It is not an indication of absolute building performance, but rather a measure of how it compares to what is considered to be the current standard.

#### *2.4.1.4 Green Star*

Green Star is a voluntary scheme launched by the Green Building Council of Australia (GBCA) in 2003. It offers a "*framework of best practice benchmarks for sustainability*" for building owners, operators, and occupants [25]. The key objectives of Green Star are *"to drive the transition of Australia's property industry towards sustainability by promoting green building programs, technologies, design practices and operations as well as the integration of green building initiatives into the mainstream design, construction and operation of buildings and communities"* [26].

A number of different rating tools are available under the Green Star banner for different building types. These are Design and As-Built, Interiors, Communities, and Performance. The rating tools assess performance based on the following categories:

- Management
- Indoor Environment Quality
- Energy
- Transport
- Water
- Materials
- Land Use & Ecology
- Emissions
- Innovation

These categories are then quantified by being divided into credits in order to award points when a particular aspect of improvement is achieved.

##### *Green Star and net zero energy*

Whilst there is no requirement in the Green Star process that buildings must be net zero, and net zero energy or carbon neutrality is not specifically rewarded, the achievement of net zero has substantial benefits for the standard certification process in the categories of operating emissions and energy use.

#### *2.4.1.5 Living Building Challenge*

The Living Building Challenge is an initiative of the Living Future Institute to advocate for the highest level of building sustainability. It promotes itself as a philosophy before a certification program. The mission of the Living Building Challenge is "*To encourage the creation of Living Buildings, Landscapes and Communities in countries around the world while inspiring, educating and motivating a global audience about the need for fundamental and transformative change*" [3]. The challenge exists in three 'typologies'; Buildings, Renovations, and Landscape & Infrastructure. Seven categories make up the challenge, and these categories are further broken down into 20 imperatives. In order to achieve Living Building status, it is necessary to accomplish all requirements of each applicable imperative (this means all 20 for buildings, 15 for renovations, and 17 for landscape and infrastructure).

Of relevance to this project, the energy under version 3.0 of the LBC requires net-positive energy. This implies a surplus of energy is required with 105% of the buildings' energy needs to be met by on-site renewables. As well as this, on site storage is also required as part of a focus on resiliency. At least 10% of lighting load and refrigeration is required to be met for a minimum of one week by back up battery storage.

### 2.4.2 Comparison of certification schemes

Roderick et al. [27] found, through computational simulation of an open-plan Dubai office building, that building energy performance and rating obtained depends greatly on the scheme used. The aim of the study was to show how building energy performance is assessed and rated under different schemes with the hope that a good basis would be formed, from which a generic and universal assessment framework could be developed in the future.

The study found that when compared to the simulated benchmark, a 7.8% improvement in energy performance was computed for the LEED scenario. This is less than the required 10.5% threshold as specified by LEED requirements and thus the building failed to be certified under LEED. For the BREEAM scheme, the simulated building scored 2 credits out of a possible 15. The results in the BREEAM scheme therefore were better than LEED but still cannot be considered a good performance. Under Green Star, a 65% reduction in energy use was predicted. This figure is significantly lower than the other cases and it is speculated that the cause of this is the calculation methodology of the Green Star scheme. The total points scored for Green Star was 11 out of a possible 20. This result is far better than LEED and BREEAM. Results are summarised below in Table 2-3.

Table 2-3 Results of energy rating comparison. From [27].

| | LEED | | BREEAM | | Green Star |
|---|---|---|---|---|---|
| | Proposed building | Baseline building | Actual building | Reference building | Base building |
| Energy consumption (MWh) | 2545.78 | 2761.86 | 1892.44 | 2044.70 | 891.57 |
| $CO_2$ emission (tons) | - | - | 776.40 | 959.01 | 386.94 |
| Energy cost ($) | 20366240 | 22094880 | - | - | - |
| Normalisation formulae | *% improvement* = 7.8% | | *EPC Rating* = 49 | | *Emissions* = 41 $kgCO_2/m^2$ |
| **Credit points** | **0 (total 10 points)** | | **2 (total 15 points)** | | **11 (total 20 points)** |

From the results, it was seen that the building energy performance rating is highly dependent on the scheme used to rate the building. Each scheme operates on different calculation and assessment methodologies and their respective credit scores reflect that. For this reason, an argument could be made that a universal and consistent assessment methodology should be developed to eliminate the inconsistencies between current schemes which provide such varying ratings. However, this study only examined one building in a location that was outside of the originating jurisdiction of all the three schemes. A larger number of studies from different locations around the world, especially Australia, the UK, and the USA would allow for a stronger conclusion about the comparative outcomes of the three schemes.

A comparative review of five rating systems was performed by Nguyen & Altan [28]. The schemes reviewed were BREEAM, LEED, CASBEE, Green Star, and HK-BEAM. CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) is a Japanese scheme developed in 2001. HK-BEAM was developed by Hong Kong’s BEAM society in 1996. The review comprised nine criteria which considered factors such as popularity and influence, methodology, data collection processes, user-friendliness, and accuracy and verification, among others. Results showed that BREEAM and LEED scored the highest based on the criteria in the study due to their well-established status and popularity, as well as proven results. The other three schemes all scored lower due mostly to their lower popularity and influence.

Whilst all building certification schemes share common aims and objectives, not all are equal in their methodologies or applications. When venturing to certify either a planned or existing building, it is important to choose a certification scheme that matches the overall aim of the buildings’ application, and also agrees well with the building codes and regulations in the location. There exists a potential need to develop a universal and consistent rating scheme that is able to assess all buildings across a range of locations according to a single methodology in order to make comparisons between buildings.

Of all schemes considered, only one requires that the building be net zero energy. The Living Building Challenge exists as a design and operation ‘philosophy’. It does not have rating criteria like all others. All 20 imperatives of all seven categories must be met in order to achieve Living Building certification. Running the scheme in this way eliminates any complications concerning points scoring and weighting factors that complicate the methodologies of other ratings systems, as was observed by Roderick et al. [27]. Of course with absolute goals as set out in the LBC, achieving Living Building certification is often more difficult than achieving a rating from any other scheme but

LBC aims to be the pinnacle of sustainability in the built environment. As such, it would not be in keeping with the philosophy of the challenge to make concessions on difficult aspects of achieving sustainability.

## 2.5 Demand-side factors in net-zero energy buildings

Whilst the overall goal of a NZEB is to produce at least as much energy as the building consumes, it is critical to note that the energy consumption of the building plays a major part in this balance. By reducing energy use as much as possible, it then becomes an easier goal to achieve NZEB status due to minimizing the renewable energy requirement, saving both required installation space and, of course, cost.

Energy consumption can be reduced through a range of measures. Implementation of efficient appliances, such as lighting and mechanical systems and the passive design of a building to work with the climatic conditions of the site, as well as the behaviour of the building occupants, can all contribute to the overall reduction in energy consumed by the building.

### 2.5.1 Energy efficiency

In a review of NZEB definitions and calculation methodologies, it was suggested that reduction of energy demand should come before renewable energy technology is considered, and that energy reduction should be a pre-requisite to NZEB development [14]. This is a recommendation shared by Pless & Torcellini [15]. Another recommendation was that EE measures should be checked periodically throughout the building's operation to ensure efficacy [14].

It has been noted that Australian residential building codes have contributed to an improvement in building shell efficiency of 29% between 1990 and 2005. This improvement, however, has been negated by the fact that average house sizes have increased and that, in absolute terms, annual energy use for space conditioning grew by 18% per household [29]. In NSW, 88% of residential dwellings use some form of heating. Bambrook et al. [29] aimed to eliminate the need for space heating and cooling systems in residential dwellings in a Sydney climate. Through simulations, it was shown that heating/cooling requirements could be reduced by 94% for a typical Sydney house built to BASIX standards. This was achieved through a combination of minimizing unwanted heat flows through building elements such as walls and windows, as well as installing appropriately placed shading around the building.

In a similar study, Griffith et al. [16] found that energy efficiency improvements in commercial buildings in the US can on average reduce consumption by 43%. This agrees with the previous trend in the literature that buildings with the greatest potential for energy conservation and efficiency improvements are the most likely to achieve NZEB status. One of the major factors in a building not achieving NZEB status is that the required roof area for an adequately sized PV system was too small. Through energy consumption reduction, the required PV capacity becomes smaller, reducing the required roof area.

#### *2.5.1.1 Building envelope*

The building envelope is defined as the barrier that separates the indoor space from the outdoors and is considered critical to the comfort of occupants, and to energy and thermal efficiency. The envelope varies significantly based on the climatic conditions of the site. A non-engaging envelope maintains a solid, separate barrier between internal and external environments. This is used where the outdoor climate is typically not hospitable such as in very low or high temperatures. An engaging envelope is one which allows interaction between occupants and the outdoors, such as operable windows and doors when the climate is comfortable. An engaging envelope typically results in a more efficient building, with reductions in HVAC loads [30], [31].

A study of a hotel building in the Mediterranean by Sozer [32] found that heating/cooling energy savings of 40% could be achieved by applying passive design principles such as appropriate thermal insulation, glazing and shading elements. The effectiveness of shading was examined in Pacheco et al. [33]. A disadvantage highlighted was that they limit the availability of daylight, increasing the need for artificial lighting. An increase in artificial light leads to an increase in heat generation within the building. It is important that these implications are considered when designing shading elements for the building envelope to ensure that excessive shading doesn’t have detrimental effects on the building energy efficiency, or occupant comfort.

For a Sydney specific climate, Bambrook et al. [29] recommended high levels of insulation in the building envelope, as well as low U-values in window assemblies to minimize heat transfer. Windows should also be sized to suit their orientation and have appropriate shading.

Pacheco et al. [33] was able to conclude that the factors that had the most influence on the final energy demand of a building are the orientation, the shape, and the compactness of the building (the ratio between external surface area and building volume). It was also found that design measures that may contribute to benefits in one season may be detrimental in another season. More research was recommended into the estimation of solar radiation in urban areas due to influences of surrounding buildings.

#### *2.5.1.2 HVAC & mechanical systems*

With a properly designed passive building envelope, heating and cooling loads, and therefore HVAC equipment requirements, should be able to be kept to a minimum [34]. Indeed in some moderate climate zones, HVAC systems can be entirely unnecessary [29]. However, the requirement for some form of heating and cooling still exists in many applications.

It has been suggested that in developed countries, HVAC accounts for half the energy use in the built environment and 20% of national overall energy use. This is seen by some as an emerging trend. In many countries, installed HVAC capacity has been rising with the desire for thermal comfort by increasingly affluent building inhabitants [5]. It is due to this growing demand for energy from the HVAC sector that significant efficiency measures need to be developed to address this. First and foremost, the system requirement should be reduced as much as possible through passive design principles as previously discussed. Secondly, the HVAC system installed should be one of energy efficient design.

#### *2.5.1.3 Lighting*

It is claimed that around 30% of a buildings' energy use can be attributed to artificial lighting. One important consideration with regards to lighting is the influence that it has on the thermal load of the building. Artificial lighting generates heat which then creates follow-on effects for the HVAC system in the building. Whilst this thermal load effect may be of benefit in winter, it will come as a disadvantage during hot periods [35].

One way to reduce the thermal effects of artificial lighting is to introduce more daylight. It has been suggested through simulation in Bodart & De Herde [36] that through optimizing the amount of daylighting in the building, the artificial lighting required can be reduced by 50 to 80%. Introducing daylighting eliminates the electrical energy required to power the light, as well as the additional energy required to remove waste heat generated by the light. The effect of daylighting on building energy savings was investigated in Krarti et al. [37]. It was found that the daylighting aperture (the product of window visible transmittance and window-perimeter floor area ratio) had a significant impact on energy savings. Increasing the daylighting aperture leads to increased energy savings. A point of diminishing returns was identified as being a daylight aperture of 0.3, and that results seem to be fairly consistent across varying geographical locations. Another study concluded that a Window-to-Wall ratio of no more than 30%-40% would also improve energy use. However above this level, the building risks overheating and glare [38].

A review of energy saving potential of electric lighting found that a reduction in lighting intensity of 50% is feasible and that for a low energy office building, a lighting intensity of 10kWh/$m^2$ is a realistic target to adopt [38]. This study focussed on a Northern European situation; but, it seems feasible that this target could be broadly adopted in a southern hemisphere situation. It was noted however, that this figure would be variable with room type.

Strategies discussed by Dubois & Blomsterberg [38] regarding the reduction in lighting energy use were concerned mostly with new technology, for instance; installing low energy fluorescent and LED lamps, new efficient ballasts, and improved luminaires.

### 2.5.2 Occupant behaviour

How the inhabitants of a building behave is considered crucial to the energy performance of the building. Their habits concerning lighting operation, ventilation preferences, and their perception of a comfortable inside environment all have a bearing on the energy used to maintain the building within preferred performance bands. With the drive towards more energy efficient buildings, occupant behaviour presents greater influence on the success of the building [39].

Hoes et al. [39] showed that user behaviour is an often neglected, yet important factor in the performance assessment of a building. A similar study was performed by Yu et al. [40] to examine the influence of occupant behaviour on energy consumption. A methodology based on cluster analysis to examine the effects of different occupant behaviour was developed by grouping similar buildings together based on four influencing factors (climate, building characteristics, number of occupants, building services and operations) that are unrelated to user behaviour. Grouping similar buildings this way ensures the separate effects of occupant behaviour are more easily identified.

Using this analysis, it was shown that in the case study, annual mean air temperature has more of an effect over building energy use intensity than mean wind speed, relative humidity, and mean global solar radiation. It was also found that occupancy numbers and heat loss coefficients of the building envelope have significant effect on energy performance and it was recommended that more attention be paid to these factors in building design.

In a survey of occupant behaviour and the control of indoor environment, Andersen et al. [41] found that the outdoor temperature had a significant impact on the opening of windows by occupants, while wind speed did not appear to affect this activity. Andersen et al. [41] noted that this finding is inconsistent with previous studies which have found that high wind speeds decreased window opening activity. This may be explained by the geographical location of the study and the complications of local wind effects not being consistent with local weather station data.

Energy audits performed in Botswana and South Africa found that the majority of a commercial building's energy use was consumed outside official office hours with the largest sources of consumption coming from HVAC systems and equipment such as computers and lighting being left on unnecessarily overnight [42].

It was suggested by Klein et al. [43] that there is potential for efficiency gains by controlling the building according to actual building occupancy, rather than the assumed design occupancy schedules that Building Management Systems typically operate from. This is especially appropriate given that it has been shown that actual building occupancy is on average found to be only one third of the design occupancy even at peak times during the day. By implementing reliable and accurate occupancy sensing equipment, great improvements could be made in building control according to the exact number of people in the building. Through real-time simulation it has been shown that HVAC consumption can be reduced by up to 20% and lighting by 30% when actual real-time occupancy data is used.

Central to the idea of sustainable buildings is the idea that buildings are low energy users. Where possible, all efforts to implement energy efficiency and conservation measures should be made before the installation of renewable generation technology. This has the benefit of saving costs in renewable energy equipment and reduces the space required to accommodate them. With studies showing that absolute energy use for space conditioning in Australian residential buildings has grown, the need for dramatic cuts in energy use is imperative. Simulations have shown that it is possible to eliminate almost completely the heating/cooling requirement for a typical Sydney dwelling through passive design principles aimed at reducing heat transfer across the building envelope.

The building envelope serves as the interface with the outside environment. It controls the physical factors such as temperature, humidity, and lighting. A high performance, engaging building envelope is central to the comfort of its occupants and the overall energy use of the building. An efficient building envelope should allow natural ventilation when outside conditions are conducive to occupant comfort. Natural lighting helps to reduce energy use, as well as contributing to occupant comfort; however, a balance between natural lighting, shading, and artificial lighting must be found. Too much natural lighting and the building may overheat – requiring HVAC systems to consume energy. Too much shading to prevent overheating, and more artificial lighting is needed.

The behaviour of occupants is one aspect of building performance that is often neglected in the literature. The way occupants interact with the building envelope by opening windows and doors, the amount of artificial lighting they feel they require, and the clothing they wear, are all elements of behaviour that contribute to the overall energy performance of a building. These are factors that require consultation during the design of the building to ensure that users of the building remain comfortable. Often, a building management system is designed to control the building according to the designed occupancy of the building. As some studies have shown, actual building occupancy is frequently as low as one third of the design occupancy. With the advent of intelligent sensing technology, it may be possible to design building management systems to control the building according the actual number of people in the building as measured by reliable occupancy sensors. This reduces the lighting and HVAC loads.

## 2.6 Supply-side factors in net-zero energy buildings

The other side of the equation of energy balance comprises energy supply. A building with greatly reduced energy demands as discussed in Section 2.5 requires the sourcing of renewable energy in order to meet its demands. Ideally this is supplied from renewable energy sources installed on site and within the building footprint. However, some high-density buildings, such as high rise commercial and residential buildings, and hospitals, have a high energy intensity compared with their building footprint. This makes on-site renewable generation difficult in many cases even with dramatic and effective demand reduction programs in place. For this reason, off-site generation options, although less than ideal, are a viable solution to aid in achieving NZEB status for all building types [15].

### 2.6.1 On-site renewable generation

The most commonly used and commercially feasible source of on-site renewable energy is Solar Photovoltaic (PV). Other sources of energy such as wind are also possibilities.

#### *2.6.1.1 Solar PV*

Given the ubiquity and abundance of sunlight in most locations on earth and historically, the rapid simultaneous increase in performance and decrease in cost of solar PV modules, achieving the NZEB goal has become more and more viable in recent years. When considering the total amount of energy reaching the earth from the sun, as well as the efficiency of solar arrays and inverters, a rule-of-thumb is that 11.25 $W/ft^2$ of power supplied to the building can be achieved. This is 46% larger than the average energy use intensity of a commercial building [31]. Given this fact, on-site solar PV is seen as a very attractive way of offsetting energy use in NZEB buildings.

*Design and installation considerations for roof-mounted PV arrays*

The major factors to be considered when designing a solar PV system for a building roof are the system size and position. The energy output of a solar PV system is largely dependent on the climatic and weather conditions that have a bearing on the amount of irradiance striking the surface of the solar panel. Irradiance is defined as the amount of power striking a surface. The units are commonly $W/m^2$. During a given time, the solar insolation may be described as the amount of energy that falls on the specified surface during that given time period. This is in often in units of $kWh/m^2/time\ period$. Often it is useful to express the time period of the insolation as a day [44], [45].

As well as the absolute irradiance reaching the surface of the earth, the position of the solar panel must be such that the irradiance reaching the panel itself is maximised. Panels should be placed in an area with minimum shading. If shading is unavoidable, it should be minimised during times of peak performance. There are two angles that must be considered in the installation of a solar array. The first is the solar azimuth angle and the second is the array inclination.

### *Solar azimuth angle*

This determines which compass direction the solar array is facing. Gevorkian [45] defines it as *"the angle measured clockwise from the true north of the direction facing the PV array. For fixed PV arrays, facing south, the azimuth angle is therefore 180 degrees clock-wise from the north".* In the southern hemisphere, the optimal azimuth angle is generally 0° i.e. facing true north. The reason for this is that in southern latitudes, the sun is always to the north of the due east-west line. In northern latitudes, the sun is always south of this line. The maximum irradiance takes place when the solar panel surface is perpendicular to the sun. For fixed panels, tilting towards the equator (north in southern latitudes, south in northern latitudes) gives the best results [45], [46]. Refer to Figure 2-1 for a visual representation of the solar azimuth angle.

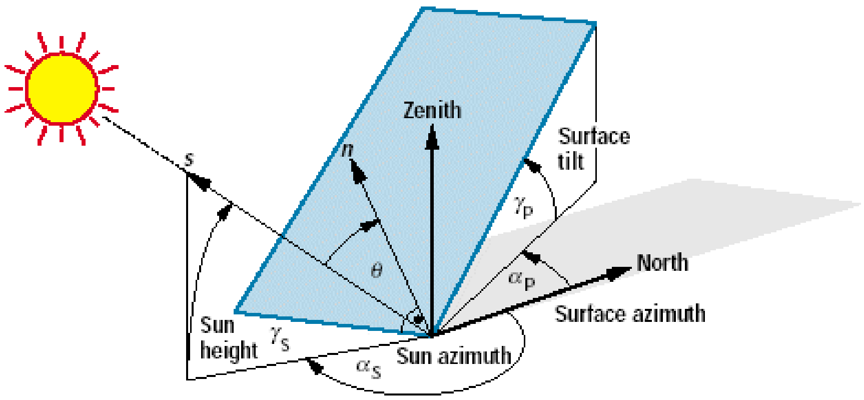


Figure 2-1 Angular relationship between the sun and a tilted flat plane [46].

### *Array inclination angle*

The inclination angle is the angle between the horizontal and the plane of the solar array. A general rule of thumb is that this angle should be approximately equal to the latitude of the installation location [47]. The latitude in Sydney is 34° south. It is recommended that panels be installed at 34° ± 10°. Since a common residential roof pitch in Sydney homes is around 25°, it is acceptable in many cases to simply mount the solar panels flat onto the roof of the dwelling. If the main loads of the building occur in winter months, it may be appropriate to increase the panel inclination to the location latitude + 15° in order to increase exposure from the winter sun which is typically lower in the sky than the summer sun. By the same token, if main loads occur in summer, decreasing the angle by 15° may be of benefit [47].

#### *Embodied Energy and Lifecycle Analysis*

For every renewable energy component that is produced, an amount of energy is needed in order to manufacture that component. This amount of energy is known as the embodied energy of the product. For solar PV technologies, a life-cycle analysis (LCA) was done by Sherwani & Usmani [48] to assess the embodied energy payback time (EPBT) and the GHG emissions created in their manufacture.

Final conclusions of Sherwani & Usmani [48] were that for mono-crystalline solar panels, the EPBT was in the range of 3.2 to 15.5 years. For poly-crystalline panels, the EPBT ranges from 1.5 to 5.7 years. The GHG emissions produced in mono-crystalline panel manufacture is 44 to 280 g-$CO_2$/$kWh_e$ while for poly-crystalline panels, emissions ranged from 9.4 to 104 g-$CO_2$/$kWh_e$.

It must also be noted that the studies examined in this review ranged over a number of years. In the rapidly advancing sector of solar PV, this is an important factor to note. As cell efficiencies and manufacturing techniques improve each year, so too does the EPBT and the GHG emissions produced. In fact, as time goes on and renewable energy penetration increases, there is a positive feedback effect on the GHG emissions produced in manufacturing as fewer fossil fuel resources are being used to power manufacturing processes.

#### *2.6.1.2 Wind*

Whilst large centralised wind farms have reached the point of technological maturity in the past few decades, the notion of small-scale wind energy is very much an emerging technology. Small turbines of less than 10kW installed in the built environment are classified as *microgeneration* [49], [50]. The challenge presented by wind generation in the built environment is that the wind resource is unpredictable and highly variable. Obstructions from surrounding structures are known to greatly diminish the potential output for a wind turbine due to the turbulence generated and reductions in local wind speed [51], [52]. Since every building and its surrounding structures are different, it is a difficult task to assess the feasibility of a small-scale wind turbine installation following a consistent methodology.

Bahaj et al. [50] addressed feasibility assessment issues using a modelling tool developed specifically for studying energy yield potential and financial payback periods. The typical wind resource characteristics of the geographical location are considered, along with a model of wind turbine performance which considers aspects such as wind speed correction factors for certain terrains, as well as the complication of wind shadow from surrounding structures and vegetation. Electricity demand for the application as well as financial and emissions considerations are used to determine the potential for monetary savings and emissions abatement. It was concluded that good high resolution wind data is necessary for an accurate assessment. Results show that wind shear and shadow effects in the built environment can reduce output by up to 50%. It is suggested that buildings situated on sea fronts and in other large, open spaces would be most suitable for micro wind generation. In addition to this though, it was suggested that it may be feasible to install wind generation capacity on large, tall buildings in urban centres due to the wind resource being stronger at increased height above ground level, as well as larger rotor diameters being possible due to the increased building size.

The feasibility of micro wind generation in New Zealand was addressed in Mithraratne [53]. Size limitations and the assurance of structural stability of installations are recognised as factors contributing to the failure of wind turbines being able to solely meet building demand. A comparison of capacity factor between centralised large scale wind farms and microgeneration wind farms highlights the reduction in potential due to interference effects. The capacity factor is defined as the measured output from a device as a percentage of its maximum theoretical output. The average capacity factor in New Zealand of a commercial, large scale wind farm is quoted as being around 45%. Through studies of urban houses in the US, UK, and Europe, rooftop wind generation capacity factors lie in the range of 4% to 6.4%. Recommendations to improve performance were to select sites with a minimum average wind speed of 5.5 m/s, and a building roof 50% higher than surrounding objects.

Overall conclusions from Mithraratne [53] were that small scale wind generation in New Zealand is suitable only in selected sites and will make only a small contribution to meeting overall electricity demands. It is recommended that conventional energy reduction and efficiency measures be implemented first to reduce demand, and that wind turbines be installed in conjunction with roof top solar in order to meet overall electricity demand. It was estimated that large scale wind farms have 11 times the generating capacity than that of small scale wind energy. However, a life cycle analysis has shown that the energy and carbon intensity of small scale wind turbines are less than grid electricity if supply chain and recycling measures are carefully considered. When considered in these terms, small scale wind technology could be of benefit to New Zealand as part of a holistic strategy of energy conservation and other small scale renewable technologies.

### 2.6.2 Load Matching and Grid Interaction

Given that renewable energy (most often solar PV) is a variable resource, it is not always the case that the energy supply generated by the building is able to meet requirements, since solar only generates energy during the day and wind only generates during times of adequate wind speed and direction. Ensuring that on-site generation matches up with on-site consumption and that energy exported to the grid is done so at a time that does not create grid stability issues due to oversupply, are factors to be considered if the NZEB concept is to be widely adopted. Matching on-site generation with on-site demand is known as load matching (LM), whilst grid interaction (GI) concerns the matching of grid export, and grid quality & stability requirements [12], [54], [55].

#### *Load Matching*

Matching the building load to the building's own generation profile ensures that NZEBs are reliant on grid electricity as little as possible. This reduces costs associated with building grid infrastructure according to peak requirements. Load matching should be considered on daily and seasonal time scales.

Daily timescales show how well the peak loads and generations match up. For a solar PV system in a residential dwelling, load and generation may not match up very well, given that typical peak loads in a house occur in the early morning when residents start their day and the early evening when residents return home. During these times, solar output is low. A typical load and generation profile is shown in Figure 2-2, which illustrates this point. For a commercial building, it may be a better situation. Occupants arrive for work mid-morning and leave mid-afternoon, with peak energy demand being within the profile of peak solar output.

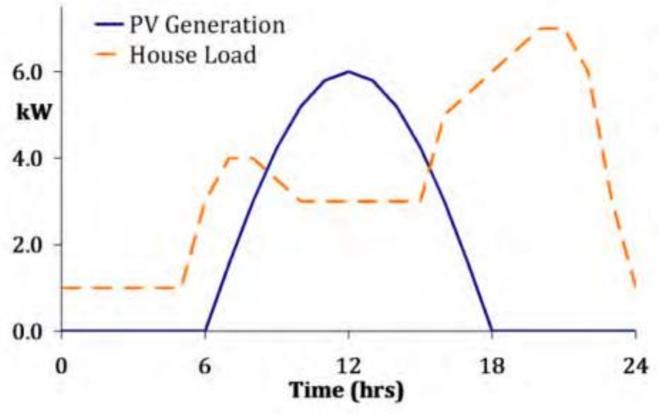


Figure 2-2 Typical load/gen profile for residential building with solar PV - [55]

Seasonal timescales provide an insight into how the load and generation profiles match between summer and winter. For the case of a solar PV system, energy demand is typically higher than summer due to the need for space heating. In addition to this, lower solar insolation means that energy generation is also lower. Seasonal load matching is therefore typically worse in winter than in summer.

A Load Match Index (LMI) is typically used to quantify the degree of load-match that is achieved in a specific case. It is defined in [55] as the average value over a time period of how well on-site generation matches the load. The load is better matched to the generation profile at a higher index. LMI is defined mathematically as follows [56]:

$$f_{load,T} = \overline{min\left(1, \frac{G(\iota) - S(\iota) - L_0(\iota)}{L(\iota)}\right)} \qquad (2.1)$$

*Where:*

- *G = Generation*
- *S = Net energy exchange with Storage (if installed)*
- *$L_0$ = Energy losses*
- *L = Building load*
- *i = time interval (hour, day, month, year etc.)*

It is noted that the LMI requires high resolution data to be accurate in order to capture the full variability of a load/generation profile [54].

Measures to improve the LMI are strategies of Demand Side Management (DSM) as well as careful design of generation capacity. By moving the time of some energy intensive activities to time of the day where generation output is at its peak, a better match between load and generation is possible. Introducing on-site storage will greatly improve the flexibility of the building to load-match, while reducing reliance on the grid in times of low generation [54].

In addition to battery storage, the placement and orientation of solar panels can also have effects on load matching. Salom et al. [55] recommends that for a net-metered residence, solar panels should be oriented east-west instead of north-south in order to take advantage of morning and afternoon sun since this coincides with times of peak demand. An office building on the other hand would orient panels north-south to catch peak midday generation potential. It is recommended that for a gross metered system, array orientation should always be so that maximum production can be achieved at all times.

An alternative to the LMI is recommended by Salom et al. [55]. The load cover factor is defined as "*the percentage of the electrical demand covered by on-site electricity generation*". Whilst both factors express the same thing, there is a technical mathematical difference between the two which results in a small numerical difference.

### *Grid Interaction*

Grid interaction refers to the variability of energy exchanged between the building and the grid. A method of indicating this is the grid interaction index. It is a measure of energy exchange variability within a year, normalised on the highest absolute value [12], [55]. The equation for the grid interaction index is given as follows [56]:

$$f_{grid} = STD\left[\frac{E(i)}{\max(|E(i)|)}\right] \tag{2.2}$$

*Where:*

- *E = net energy exported to the grid*
- *i = time interval*

When compared with the load match index, the grid interaction index is the ratio of net grid metering over a given time period, to the maximum or minimum in the annual cycle [57]. If the index is positive, it describes a net positive energy building, while a negative index signifies a net negative energy building. It is a measure of the fluctuation of energy exchange between building and grid and has nothing to do with the amount of grid electricity required by the building [54], [55].

The grid interaction index is said to be sensitive to time intervals. High resolution data should be used where possible in analysis of grid interaction [12]. In Salom et al.[56], it is argued that NZEBs at high penetration levels may have detrimental impacts on the grid at small timescales by contributing to peak grid loads when on-site generation becomes insufficient. High resolution data is also useful for making forecasts of building energy use and generation in order to predict the grid interaction index. Through forecasting this, grid stability and power quality issues can be anticipated and planned for in advance of complications occurring [55].

### 2.6.3 Off-site Renewable Generation

Buildings with high energy intensity such as hospitals and shopping centres may not have the ability to install sufficient renewable energy capacity on the building site to meet all demands. In this case, renewable energy must be generated off-site and transported from the grid to the building. Pless & Torcellini [15] recommends that energy intensive buildings still install as much on-site capacity as possible, but that the balance may be made up through the purchase of Renewable Energy Credits (REC). It is stressed that just purchasing REC's to offset all building energy demand is not an acceptable strategy for NZEBs. All efforts must be first made to reduce consumption and introduce efficiency measures [11].

A lifecycle financial comparison of on-site and off-site supply options found that annual costs of on-site supplies decrease when higher energy efficiency measures are implemented. In the case of off-site options, annual costs increase. It can be concluded from this that energy efficiency should take priority over on-site energy generation capacity in order to achieve the cost-optimal scenario. For the case of off-site generation however, it was found to be most cost effective to invest in generation capacity than in energy efficiency [58]. This finding is at odds with the definition philosophy defined by Torcellini & Pless [11] as the overall objective of a NZEB is not only to offset all energy demand with renewables, but to reduce overall demand and encourage a less energy intensive built environment.

### 2.6.4 Distributed Generation & Microgrids

The general concept of distributed generation (DG) is to locate the generating infrastructure close to the load, often on the consumer side of the grid. Whilst there are many varied definitions of DG currently in the literature [59], the underlying concept is one of direct relevance to NZEBs. It is recognised that as NZEB penetration becomes larger, there will be power quality implications for the grid. Salom et al. [55] state that at low penetration, NZEBs can be of benefit to the utility grid because they decrease losses and smooth out voltage profiles. However, at higher penetration, large reverse power flows may occur due to surplus energy exports from NZEBs as well as increased local losses. This causes the overloading of grid components and necessitates the need for the grid specification to be increased. Since grid planners need to design for the peak grid load, rather than the average, steps must be taken to ensure large scale export events from a number of NZEBs do not contribute to increased peak loads on the grid [55], [60].

A way of managing the potential implications of DG is to approach it from a systems perspective. Generation and loads can be broken down into sub-systems called microgrids [61]. By taking this approach, it is possible to control DG on a local level. Microgrids can be isolated through intentional islanding from the main utility grid during times of disturbance in order to be able to supply the microgrid using its own resources [62].

#### *Implications of Intermittent Resources at High Penetrations*

The flexibility and rapidly declining cost of solar PV means that in many cases, they can be constructed very close to the load without the stringent and time consuming process that is associated with large centralised power generating facilities. This makes for a more efficient system by cutting down on transmission losses. However, their intermittency due to diurnal cycles and weather variations means that solar poses new challenges to grid operators. Large reverse power flow patterns spell changes for the grid protection and control strategies [63]. Intermittency requires more regulation of ramping requirements for the grid. As wind and solar resources depend on highly variable weather conditions, they sometimes experience sudden changes in power output due to wind speed and irradiance changes. Impacts on distribution networks from solar PV DG resources are described in Katiraei & Aguero [64]. These impacts include voltage rise and unbalance, equipment and component overload, and increased losses from reverse power flow. The extents of these impacts are expected to increase with the rise in penetration levels, as well as grid specification in the installed location. It is suggested that new generations of solar inverters would have the capability to address many of the challenges discussed by regulating voltage and having ramp-rate control.

## 2.7 Building Performance Modelling Options

Building performance models are a valuable tool that can be used to evaluate the effects of different building designs, technologies, and control strategies before the construction of a building. With the aid of a model, important decisions can be made early in a project which can increase building performance, reduce costs, and save time [65].

Several techniques are available to engineers for building modelling. Physical modelling techniques can be broken down into several categories. The Computational Fluid Dynamics (CFD) approach is arguably the most comprehensive method but is complex and requires significant computational resources and a highly skilled operator. The zonal approach is a simplification of the CFD method. It divides the building into different 'zones' where one cell is a division of a room. Physical equations are solved for each zone rather than for each element of the mesh as with the CFD approach. Whilst not as accurate or comprehensive as CFD, the zonal approach gives good results when calculating air temperature, pressure, and velocity distributions within each zone whilst still retaining more manageable computing requirements. The multi-zone or nodal approach is a further simplification of the zonal approach. It assumes that each room is one cell and is a homogeneous volume with uniform state variables. Advantages of this technique are that it is able to compute simulations over very large time periods within a minimum of computation time. The estimation of energy consumption and space temperature are well suited to this technique [66]. Table 2-4 gives a summary of the different physical modelling techniques showing applications, as well as advantages and disadvantages.

Table 2-4 Summary of physical modelling techniques from [66]

| Physical technique | Specificity of each technique | Application field | Advantages | Drawbacks |
|---|---|---|---|---|
| CFD method | One cell = a control volume (3-D); Local state variables | Contaminant distribution; Indoor air quality; HVAC systems | Detailed description of the fluid flows occurring inside the building; Large volume zones | Huge computation time; Complexity of the model implementation |
| Zonal method | One cell = a division of a room (2-D); Local state variables | Indoor thermal comfort; Artificial and natural ventilation | Spatial and time distribution of local state variables (temperature, concentration, pressure, airflow) in a large volume | Large computation time Requirement of a detailed description of the flow field and flow profiles |
| Nodal method | One cell = a room (1-D); Uniform state variables | Determination of the total energy consumption/the average of the indoor temperature/the cooling or heating load; Time evolution of the global energy consumption/ the space-averaged indoor temperature | Multiple zone buildings; Reasonable computation time; Easier implementation | Difficulty to study large volume systems Unable to study local effects as heat or pollutant source |

It can be seen from Table 2-4 that the most useful technique for a study of NZEB's is the multizone/nodal technique. This is because the focus of the modelling is on energy consumption and thermal loads. Therefore more detailed and intensive analysis such as that provided by CFD is unnecessary. Similar reasoning is given in [67] regarding the use of simplified modelling tools. The study of long term trends and system comparisons are well suited to the nodal method. It has been determined from the literature that the most common tools for energy modelling are DOE-2, eQUEST, BLAST, and EnergyPlus. These are described and compared below.

### 2.7.1 DOE-2

DOE-2 is an energy analysis program for whole-buildings. It can be used to analyse energy consumption and efficiency of each building zone on an hourly basis. It considers the building layout, construction, operating schedules, and building systems combined with weather data to perform hourly simulations. However, a high degree of computational knowledge is required to operate effectively given there is no graphical user interface. Many third party interfaces have been developed to work with the DOE-2 simulation engine [68]–[70]. One of these interfaces is eQUEST.

### 2.7.2 eQUEST

This tool utilises the DOE-2 simulation engine to perform comparative analysis of different building designs. A building creation wizard allows the user to create a building model with guidance from the program. The graphical user interface aids the user both in development of the model, as well as display of results. The results display module allows the user to view the results of multiple simulations side-by-side [68], [69].

### 2.7.3 BLAST

Building Loads Analysis and System Thermodynamics (BLAST) is another hourly simulation tool that offers analysis of buildings and HVAC systems, and provides results regarding energy use and efficiency. Detailed heat balance algorithms allow for the assessment of thermal comfort; however a high level of expertise is required to operate it. BLAST first predicts the hourly space conditioning loads within the building based on the weather data, temperature control strategy, and the heat transfer interactions throughout the building envelope [69], [70].

### 2.7.4 EnergyPlus

Arguably the most advanced of all tools discussed; EnergyPlus was developed from a combination of the best features from BLAST and DOE-2, whilst including the addition of a range of unique new features. Like BLAST and DOE-2, EnergyPlus is primarily a simulation engine with little in the way of a graphical user interface. However third party GUI's such as DesignBuilder have been developed to take advantage of EnergyPlus's capabilities.

One feature of EnergyPlus that was lacking in both BLAST and DOE-2 was the ability for the simulation to provide feedback between the HVAC module and the load calculations module. This lack of feedback leads to inaccurate temperature prediction which has a large influence over HVAC systems sizing, occupant comfort, and energy use [71].

The basic assumptions in the underlying thermal zone calculation are that the air in each room is modelled as being of uniform temperature, and that surfaces in the room are of uniform temperature, and have internal heat conduction. Time steps of less than an hour are possible with the default being 15 minutes.

Whilst there are many advantages to EnergyPlus such as its potential for more detailed simulation methods to be integrated where necessary, and its CAD interfacing capabilities to allow geometry to be easily developed, it is difficult to use without a graphical use interface. Third party GUI's such as DesignBuilder make EnergyPlus a much more versatile tool.

### 2.7.5 DesignBuilder

DesignBuilder (DB) is a modular graphical user interface utilizing the EnergyPlus simulation engine. The modules available are:

i. 3D modeller – to enable fast construction of geometric and physical attributes of the building
ii. Visualisation – enables designers to produce rendered images of the model
iii. Certification – DB generates Energy Performance Certificates and building regulations compliance checks in accordance with UK regulations
iv. Simulation – the EnergyPlus simulation engine used for energy and comfort analysis. It is able to provide data such as energy consumption, carbon emissions, room comfort, and temperature distribution on sub-hourly time steps.
v. Daylighting – DB is able to report on daylight factors and illuminance data to assess the natural light levels and visual comfort within the building.
vi. HVAC – the HVAC capability of EnergyPlus is expanded into a graphical environment in DB. Large libraries of HVAC components and systems are available to choose from or systems are able to be specified from scratch.
vii. Cost – building construction and operating costs can be estimated based on a range of assumptions within DB
viii. LEED – DB is able to assess the building model against LEED requirements and give a summary report providing the data required for LEED energy credit submissions
ix. Optimisation – identification of design options based on criteria of cost, energy, and comfort performance are possible

## 2.8 Summary

Given the accelerating impacts of human induced climate change being observed worldwide, it is crucial that decarbonisation of the built environment happens quickly. Net zero energy buildings provide a promising solution to decarbonisation of both the built environment and our transport sector, with personal electrical vehicles becoming more commonplace. Our buildings can provide surplus energy to charge electric vehicles. Meaningful cuts to emissions are possible through the widespread adoption and development of net zero energy buildings.

A Net Zero Energy Building (NZEB) is simply one that produces at least as much energy as it consumes. There are many ways to define the 'zero' balance, depending on the objective of the building under study and the regulatory environment in which it is built. Four common definitions studied in the literature are site, source, cost, and emissions.

Several factors such as balance metric and reporting period must be considered in order to define which kind of NZEB the building is. This definition has a bearing on the data required for reporting and will also affect the final outcome determining the success or failure of the NZEB.

A need exists to better understand how best to achieve NZEB status in buildings, both new buildings and retrofits. A number of organisations, government and non-government, have responded to the increased awareness of building sustainability by developing codes, standards, and rating systems designed around a framework of sustainability factors such as energy use, water use, and building materials. Whilst all schemes share similar objectives and methodologies, minor differences in implementation exist and are a reflection of the regulatory environments in which they were designed. No scheme apart from the Living Building Challenge requires that buildings be net zero energy. However, significant benefits would be achieved for all schemes as a side effect of being a NZEB in terms of energy performance.

By reducing energy use as much as possible, achieving NZEB status becomes easier due to minimization of the renewable energy requirement, saving both required installation space, and of course, cost. Energy demand can be reduced through a range of measures. Installation of efficient appliances such as lighting and mechanical systems and the passive design of a building to work with the climatic conditions of the site, as well as the behaviour change of the building's occupants, can all contribute to the overall reduction of energy consumed by the building.

The most commonly used and commercially feasible source of on-site renewable energy is solar photovoltaic (PV). Fossil fuel driven micro-turbines and cogeneration plants are also options, but are less attractive when the motivation is to reduce the overall environmental impact. Other sources of energy such as wind are also possibilities. Given the ubiquity and abundance of sunlight in most locations on Earth and historically, the rapid simultaneous increase in performance and decrease in cost of solar PV modules, achieving the NZEB goal has become more and more viable in recent years.

Buildings with high energy intensity such as hospitals and shopping centres may not have the ability to install sufficient renewable energy capacity on the building site to meet all demands. In this case, renewable energy must be generated off site and transported from the grid to the building. Guidelines recommend that energy intensive buildings still install as much on-site capacity as possible, but that the surplus may be made up through the purchase of Renewable Energy Credits (REC).

From reviewing the literature concerning net zero energy building definitions, reporting strategies, certification schemes, and demand and supply side factors, a number of areas have been identified which warrant further research. Primarily, the overall consensus in the literature is that for a building to succeed in achieving net zero, it must reduce its demand as much as possible to have the best chance. The practical barriers to installing sufficient generating capacity in a building are much larger when little effort has been made to reduce demand. Improvements to the building envelope of some commercial buildings around the world have been found to reduce energy demand significantly. Improvements such as upgrades to thermal insulation and glazing, as well as the introduction of shading elements can improve energy efficiency. It is noted however that the net benefit of some of these measures may not be positive due to seasonal effects. Careful design and planning would ensure that a net benefit is achieved.

A case study of net zero energy buildings and their energy sensitivity to different building technologies is an area of research that would be of interest. Currently case studies of net zero buildings are not common, especially in the context of an Australian climate. Quantification of the contribution of energy efficiency technology and strategies through building modelling would provide valuable insight into meeting net zero energy in existing buildings. These factors are worthy of investigation.

# Chapter 3 Methodology and Description of Case Studies

## 3.1 Introduction

With net zero energy buildings being seen as a promising solution to emissions reduction in the built environment, it is important to be able to design and construct a cost effective and higher performing net zero energy building. To achieve this, a greater understanding of the design and operation of high efficiency buildings is required, especially the interaction between different building elements and their overall net impact on energy use. The differences between efficient buildings and more conventional designs should also be understood, to be able to quantify their comparative potential benefits and disadvantages.

Three buildings studied here (two of which are recently completed net zero energy buildings) provide an opportunity to study these new types of buildings and provide comparisons to the energy use of more typical commercial buildings at similar locations. Building performance simulation provides a means to better understand these issues. By modelling all three buildings and comparing simulation results to real weather and energy data collected over a period of time, the models are able to be validated and considered to be of practical significance. Undertaking simulations of all building models while implementing varying degrees of energy efficient building technology and operating strategies will provide an understanding of the influence of these technologies and strategies, relative to each other, as well as on each buildings overall performance. This chapter provides a detailed view of the modelling and simulation methodology, as well as an introduction and background to each of the three test cases used for simulation.

## 3.2 Uncertainties in building energy modelling

A common problem encountered in building performance simulation is that of a gap between simulated performance and measured real performance. There can be many contributing factors to this ‘performance gap’ but most commonly, the source of error stems from inaccuracies associated with assumptions used in place of hard-to-measure building inputs.

Many existing buildings lack detailed information in a number of areas:

- Complete as-built construction drawings from which a detailed and accurate geometrical model can be developed. Many buildings undergo a multitude of façade and structural alterations of varying significance throughout their lives and quite often as-built drawings are either not comprehensively updated, or they are not kept on file by facilities managers. This can make modelling of the building difficult and the modeller must rely on certain assumptions and default values, e.g. the type and extent of building insulation or glazing performance figures where exact glass specification is unknown;
- Sub-metering capabilities with which to assess the baseline energy consumption of building services are often lacking. Depending on the size and complexity of the building's electrical infrastructure, it may be possible for the modeller to install temporary metering equipment in order to obtain consumption data of selected electrical circuits with which to validate the building model. Where this is not feasible, simulation assumptions based on building code guidelines may be used, but there is little certainty that this assumption would be accurate in the specific case;
- Occupant behaviour is possibly the largest source of uncertainty in building performance simulation due its stochastic nature and large influence over energy consumption, particularly in smaller buildings. Building occupancy and equipment usage schedules are highly individual factors and are often very specific to the building tenant. Building occupancy is also one of the most difficult variables to measure. Occupancy sensors in buildings are able to tell a modeller if a room is occupied, but not by how many people or what their activities are. Depending on the type of building, occupancy may be highly variable throughout the working week or even work day. Because of this, developing a 'typical' occupancy schedule to use in a building performance simulation can be very difficult and is a major source of uncertainty.

A poorly commissioned or maintained building will also contribute to modelling inaccuracies. If the building is not operating according to designed performance levels, then certain assumptions used in the model which are typically drawn from technical specifications will not accurately reflect the reality.

### 3.2.1 Weather data in model validation

For a building model to be useful and provide a meaningful contribution, it must be validated to best represent the real operation of the building. Simulation of a building should be performed according to a Typical Meteorological Year (TMY) [72]. A TMY is a year of weather data at hourly intervals, collated from a dataset of many years to best represent a typical year of data for the specified location. TMY data does not include extreme weather events as it is intended to best represent the building under normal operating conditions. TMY data is not suited to validating a building model. For validation, the model must use actual historical weather data in order to match the response of the model to the response of the real building data during a particular time period. By comparing the internal temperature profile of the building to that of the model on the same day using recorded weather data as a model input, it is possible to tune the building model to best match that of the real building without uncertainty due to weather factors.

Once validation has been achieved using real weather data, TMY data should be used to carry out the overall intended objectives of the building model. Using real weather data for this purpose will only provide results specific to the weather that was experienced over the period for which data is available. Typical representative results for the building can only be achieved using TMY or other weather data created from averages of long-term historical data.

### 3.2.2 Model validation methodology

To validate a building model, several aspects of it should be compared to real data taken from the building. For this study, model validation was completed using internal temperature profiles and daily energy use of various loads, as indicated in Figure 3-1. With accurate historical weather data available, uncertainties surrounding weather conditions can be more or less eliminated, making for a valid comparison between the identified parameters.

#### *Temperature profiles for building modes*

Historical periods representing each of the three building modes (cooling, heating, and natural ventilation) were selected where data was available and simulations were run for those times. The actual indoor temperature profile was compared with that generated by the simulation. A match between the measured temperature profile and that of the model should provide an indication of how well the model represents the thermal performance of the real building.

### *Daily energy use*

Due to stochastic factors such as occupancy which are difficult to model accurately, the energy use of building elements such as lighting is unlikely to match actual usage profiles of the building over a short timescale. However, a properly calibrated model should exhibit similar daily energy use when compared to the buildings' measured energy use. Daily lighting and IT loads were compared to the model for periods where data from the building was available.

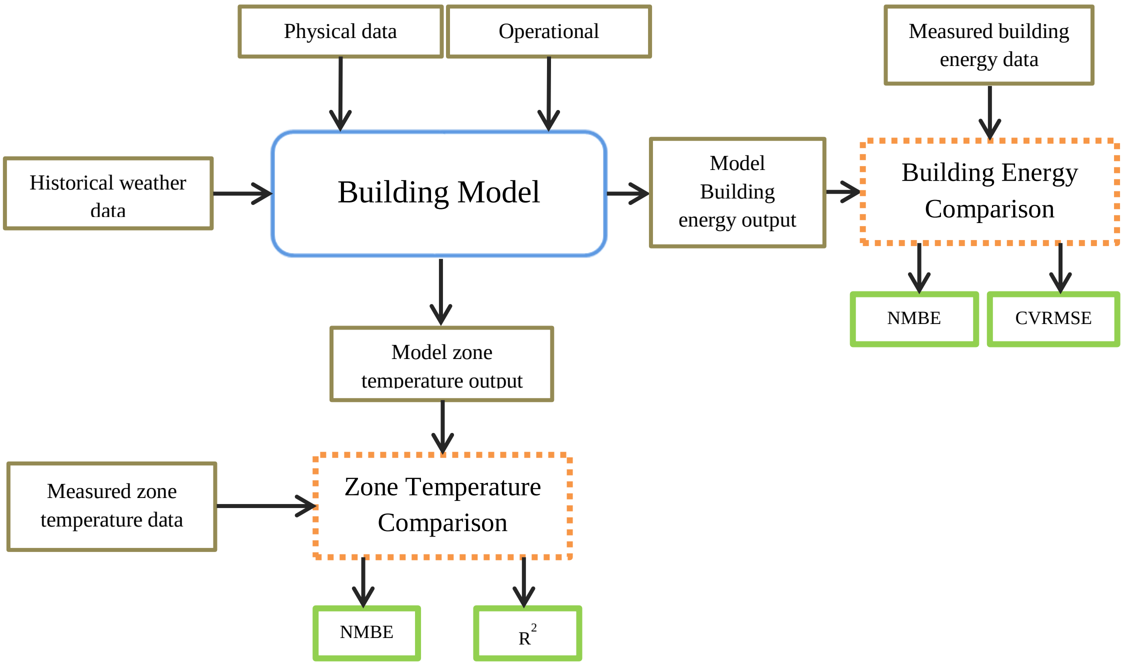


Figure 3-1 Model validation methodology.

### *Error Quantification*

Error quantification for temperature profiles was completed using the Normalised Mean Bias Error (NMBE) and the coefficient of determination, $R^2$. NMBE is a measure of how close the modelled data fits the measured data and is expressed as a percentage. An NMBE close to zero is desirable. It is the ratio of the sum of the residuals to the sum of all measured data points. NMBE is given by equation (3.1) from [73]:

$$NMBE = \frac{\sum(y_{measured} - y_{modelled})}{\sum y_{measured}} \times 100 \quad (3.1)$$

*Where:*

- $y_{measured}$ = *measured data point*
- $y_{modelled}$ = *modelled data point*

A maximum NMBE of 15% was considered as satisfactorily accurate for the thermal validation of the model. As thermal accuracy of the model is secondary to that of energy and serves only to confirm the correct behaviour of the building model, there are no specific acceptability criteria being followed for the thermal model. An NMBE of 15% was chosen as this corresponds to an average residual of around 1-2°C, which is within the margin associated with measurement error such as calibration or position of measurement. Regardless of the allowable error selected the model will always be more accurate in some sections of data than others owing to unpredictable events such as occupant override of building HVAC systems or equipment malfunction. Additionally, the coefficient of determination, $R^2$, was calculated from a scatter graph between measured and modelled temperature variables. This helped to quantify the degree of correlation between the model and the real building and aided in setting levels of confidence in the model.

The error associated with the energy models was quantified according to the method outlined in ASHRAE Guideline 14-2002 [73]. This method relies on measured energy data being compared to the model output using both the NMBE and the Coefficient of Variation of the Root Mean Squared Error (CVRMSE). The CVRMSE is a measure of how well the model fits the data. A lower CVRMSE value suggests that the model is a better fit. It is the ratio of the square-root of the Mean Bias Error to the average of all measured data points.

CVRMSE is given by equation (3.2):

$$CVRMSE = \frac{\sqrt{\overline{(y_{measured} - y_{modelled})^2}}}{\bar{y}_{measured}} \times 100 \quad (3.2)$$

*Where:*

- $y_{measured}$ = *measured data point*
- $y_{modelled}$ = *modelled data point*
- $\bar{y}_{measured}$ = *average of all measured data points*

The CVRMSE is used in conjunction with NMBE to eliminate the fact that NMBE may be influenced by offsetting errors. ASHRAE Guideline 14 states that an energy model may be declared valid if the NMBE is ±10% and the CVRMSE within ±30% when using hourly data or 5% to 15% when using monthly data. Although daily data is being used here, the 15% limit was chosen for the selected case study simulations. The building models developed in this study are intended to be generally representative of the real buildings so that general behaviour can be simulated.

## 3.3 Simulation methodology

Development of a simulation methodology must reflect the overall objectives of the project. As whole-building energy use was of particular focus here, overall energy consumption is the main metric to be used to indicate results of different simulations. However a deeper understanding may be gained by looking at a system or sub-system level. In a system as complex as a building, there are many combinations of variables that may have an effect on energy use. It would be impractical to investigate all of them for the purposes of this thesis. Five building elements were selected to be investigated in terms of their technology and their implementation. The proposed simulation methodology is outlined in Figure 3-2.

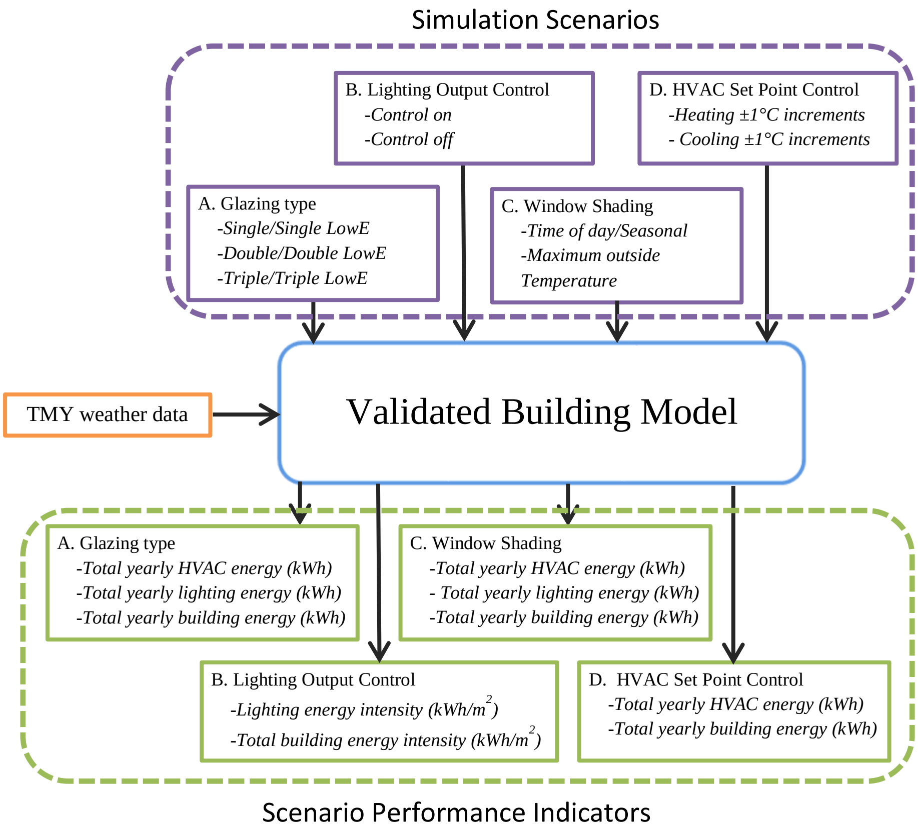


Figure 3-2 Proposed building simulation methodology.

In some cases, it is necessary to maintain a constant level of certain parameters in the interests of occupant comfort. It would not be acceptable for a building to achieve large energy savings if this comes at the expense of occupant comfort and building functionality. For the case of lighting, it is necessary to keep an adequate and reliable standard of illuminance. Where shading is concerned, both lighting and IEQ are influenced and thus must be maintained where different shading technologies and control strategies are investigated. In some cases, occupant comfort and functionality are the variables being tested, rather than maintained. For the investigation of HVAC, the temperature bands are to be varied to determine the amount of energy that could be saved if occupants were willing to tolerate slightly warmer conditions in summer and cooler conditions in winter.

The following figures outline the procedures followed for the simulations of each building model.

### 3.3.1 Glazing

Changing the type of glazing is likely to have an impact on the solar heat gains in the building throughout the year. Single glazed or poor performance double glazed windows are likely to introduce more heat to the building throughout summer, driving up cooling loads. Figure 3-3 outlines the simulation process to be carried out.

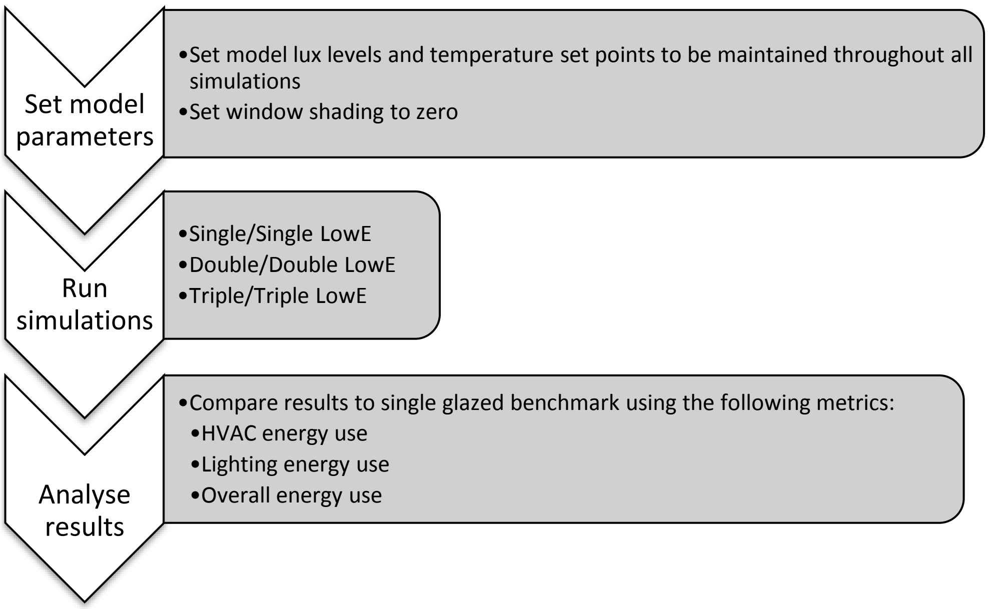


Figure 3-3 Glazing simulation procedure.

The overall annual impact on HVAC energy use will be tested here as well as the impacts on other related electrical systems such as lighting. It is hoped that the outcome will be a quantification of any benefits of high quality double glazing and whether triple glazing could extend those benefits in any significant way.

#### *3.3.1.1 A description of glazing types*

It is important to outline the different types of glazing examined in this study to give some background and insight into why these building elements are being simulated.

##### *Single Glazing*

A conventional single pane of glass mounted in a frame typically constructed of timber of aluminium.

##### *Single LowE Glazing*

Similar to a single glazed window, but using low emissivity glass (LowE). LowE glass has a thin coating deposited on its surface. Different coatings can have different effects but typically, all coatings cut down on the amount of infrared light being transmitted through the pane. This has the effect of reducing radiant heat transfer.

#### *Double Glazing*

A window system consisting of two panes of glass mounted in a frame typically constructed of timber of aluminium. The gap between each pane of glass is commonly filled with air. Argon can also be used to provide improved insulative properties

#### *Double LowE Glazing*

Similar to conventional double glazing, but using LowE glass as previously described for one or both panes.

#### *Triple Glazing*

Similar to a double glazed window unit, however three panes are used instead of two.

#### *Triple LowE Glazing*

Similar to conventional triple glazing, but using LowE glass as previously described for one or all three panes.

### 3.3.2 Lighting

Whilst there are many different types of lighting technology available, their impacts on electrical loads are relatively easy to calculate without the need for modelling given that their electrical inputs are generally proportional to their light outputs. Instead, the operation and control of lighting will be simulated as this relies on many different variables. Daylight control involves the use of a photosensor to detect the amount of natural light in the room. The lighting control system interprets the reading given by the photosensor and decides how much artificial light is necessary based on preset lighting level requirements.

Occupancy also plays an important role in lighting operation. A modern controlled lighting system will be occupancy-driven. Passive Infrared (PIR) sensors will detect occupancy and automatically turn on artificial lights if they are necessary. An additional simulation scenario of determining the energy savings due to automatic lighting control would be of great interest. However occupancy can be difficult to predict in many situations (especially for sparsely populated buildings) and the models presented here do not have the capability to model stochastic factors such as occupancy. For the purposes of this study, lighting operation is driven by a predetermined occupancy schedule. Figure 3-4 outlines the simulation and analysis procedure to be followed.

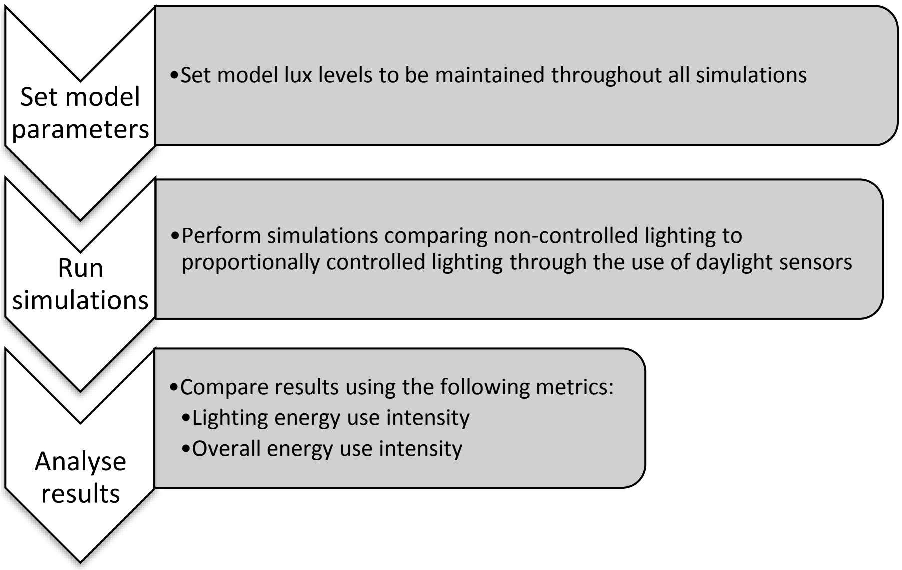


Figure 3-4 Lighting simulation procedure.

The lighting schedules for each building model are shown below in Figure 3-5.

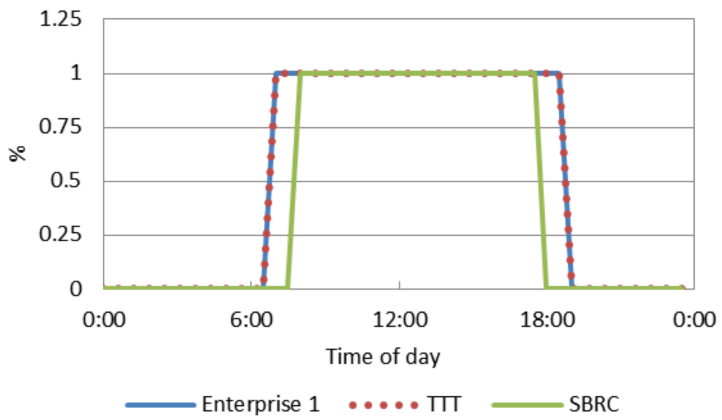


Figure 3-5 Building model lighting schedules

The occupancy schedules for each building model are shown below in Figure 3-6. Occupancy and building systems schedules have significant influence over the results of a simulation and are key factors in developing an accurate and validated model.

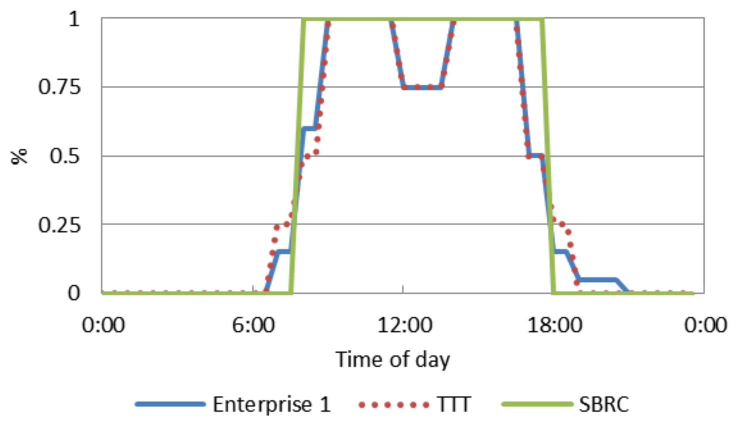


Figure 3-6 Building model occupancy schedules

### 3.3.3 Window Shading

Local shading of windows using architectural elements, such as side fins, overhangs, and louvres is driven by well researched architectural design and depends heavily on the building site location and orientation. This would be a challenging building element to model and drawing general conclusions from the results would be problematic. However, window shading in the form of blinds or curtains can be modelled with expected conclusive outcomes.

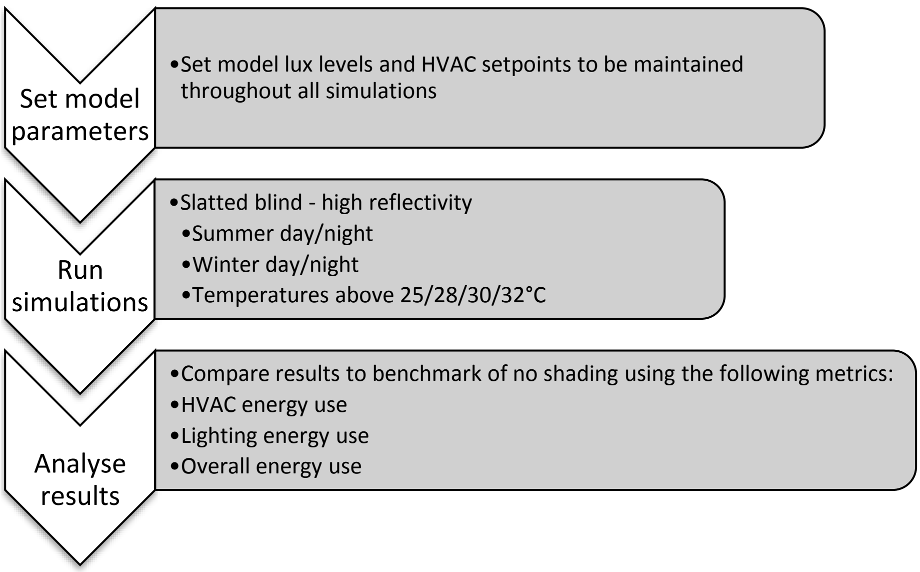


Figure 3-7 Window shading simulation procedure.

Rather than simulation of the best type of shading, which could have many combinations, the operation of the window shading has been chosen for modelling instead, as outlined in Figure 3-7. A consistent shading type has been chosen as a slatted blind with high reflectivity slats. The reason for this is that this type of shading is common in many commercial buildings. The scenarios to be tested are based both on the season and time of day, as well as the outdoor temperature. The results will be compared on a whole building energy use level, as well as the impacts on lighting energy use (with less natural light in summer, this will increase lighting loads) and HVAC use.

### 3.3.4 HVAC

Since detailed HVAC systems in DesignBuilder are quite complex to model, a simplified model will be developed for the case study buildings. A result of this is that the HVAC energy consumption of the model is likely to be only nominally comparable to that of the real system. However, the relative performance effects of the model system amongst the simulated scenarios will still be valid and conclusions about energy consumption changes may still be drawn back to the real system.

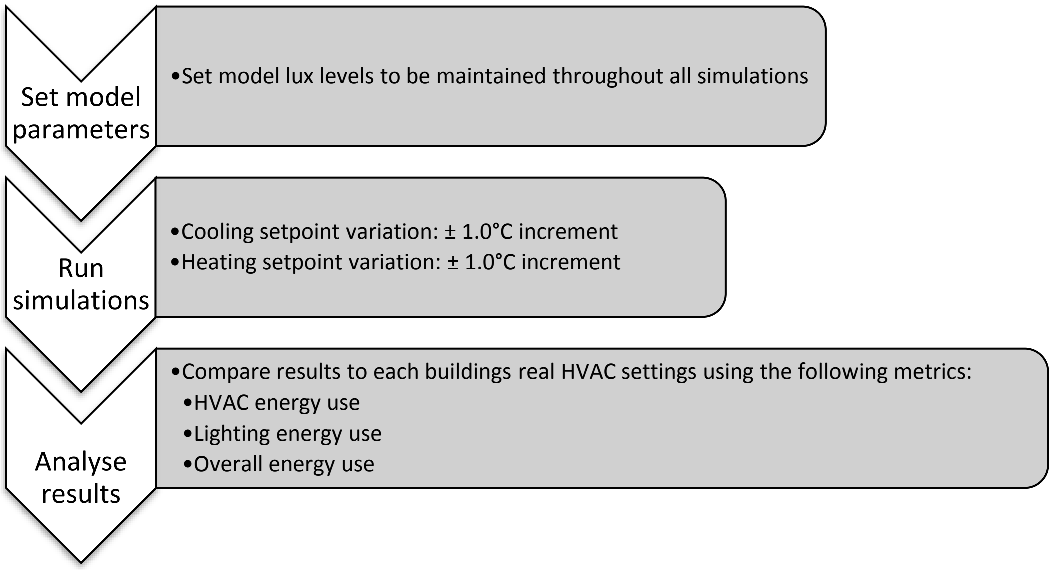


Figure 3-8 HVAC simulation procedure.

Keeping HVAC simulations independent of equipment specifics enables general conclusions to be made about potential energy consumption in buildings. Varying the HVAC setpoints is often quoted as an effective way of reducing energy consumption [74]. Simulations performed in this study will aim to quantify this effect for the net zero energy test cases as well as more generally. Figure 3-8 outlines the simulation process to be carried out. The HVAC operation schedules used in each building model are shown in Figure 3-9.

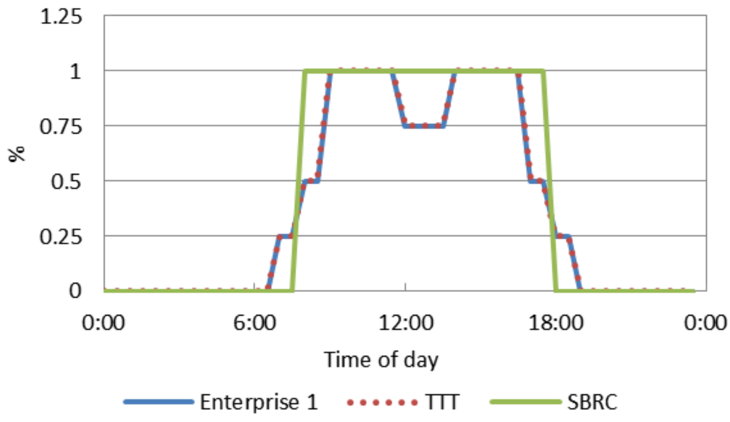


Figure 3-9 Building model HVAC schedules

## 3.4 Sustainable Buildings Research Centre – University of Wollongong

The University of Wollongong's Sustainable Buildings Research Centre (SBRC), shown in Figure 3-10 was designed to bring together a range of disciplines with the goal of addressing the challenge of making Australian buildings more sustainable. The location of the 8,000 $m^2$ site of the building is at the Innovation Campus of the University of Wollongong. It is a 2,600 $m^2$ double story research building with exhibition spaces, education and training centres, as well as academic offices and high-bay laboratories. With the building axis running east-west and separation between the two main wings, maximum passive ventilation and natural light are utilised. The first of the two wings is a 1,700 $m^2$ building housing academic offices, education and training spaces, as well as a flexible working space and public exhibition centre. The second wing is a 900 $m^2$ structure housing high-bay laboratories and much of the HVAC plant used in the building.


Figure 3-10 Sustainable Buildings Research Centre (SBRC).

### 3.4.1 Building façade

Key features of the building façade of the SBRC building are the reverse brick veneer construction, which differs from conventional brick veneer construction by placing the thermal mass on the inside of the building, within the insulated envelope. This provides a more stable indoor temperature [75]. A mixture of timber and steel cladding is used on the exterior of the building. An example of the insulated timber and steel façade section is shown in Figure 3-11.

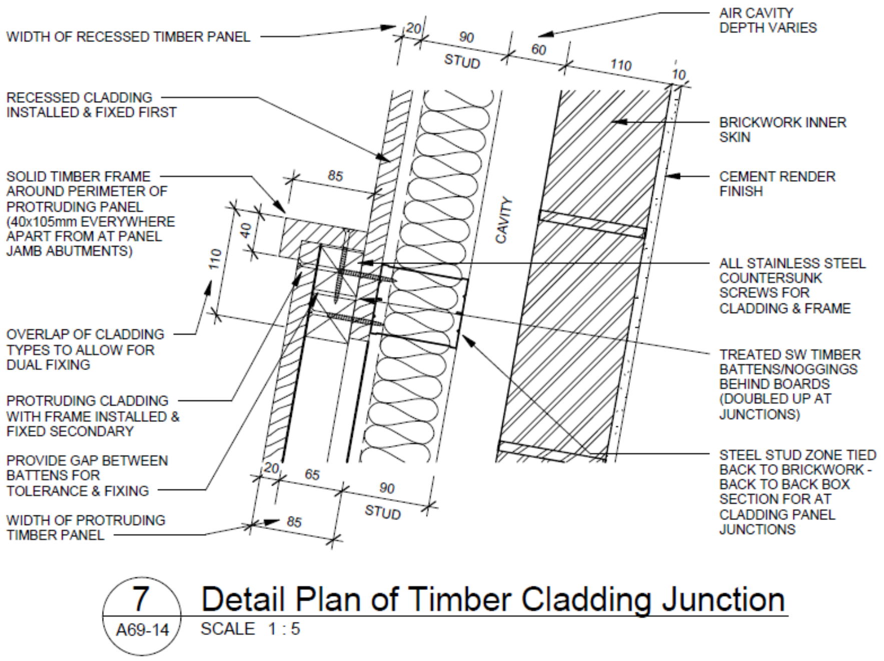


Figure 3-11 SBRC building façade section example [76].

The building is insulated to a high degree. Concrete slabs are insulated to a minimum R-value of 3.2 $m^2K/W$. External walls are insulated typically with 90 mm thick polyester batts with a minimum R-value of 2.8 $m^2K/W$. Roof insulation is specified as a minimum R-value of 3.2 $m^2K/W$.

Primarily, high performance double glazing is used for all external windows, glazed doors, and curtain walls. Windows are fitted with actuators controlled by the BMS when natural ventilation is deemed necessary.

### 3.4.2 Energy efficiency

The SBRC achieves its high level of energy efficiency thanks to a range of design choices and cutting edge technologies.

The building is laid out in an H-configuration. This helps to optimise natural ventilation and maximises natural light throughout the building. A mixed-mode ventilation system utilizing a ground heat exchanger and in-slab hydronics system reduces the HVAC energy intensity significantly over a more conventional system. Low energy lighting systems with intelligent controls are used where daylight levels are insufficient. PIR sensors detect if a room is occupied and photoelectric light sensors detect whether daylight levels are low enough to warrant the use of artificial lighting.

### 3.4.3 Local generation

Solar PV arrays are installed on both north and south wings of the SBRC providing a total capacity of 163 $kW_p$. The south wing rooftop holds most of the installed capacity with 120 $kW_p$ whilst 43 $kW_p$ is installed on the north wing of the building in two different inclinations – 30° and 70°.

In addition to the conventional PV installed at the SBRC, an experimental array of Building Integrated Photovoltaic Thermal (BIPVT) panels has been installed. Ducts installed beneath the panels harvest the heat absorbed by the PV panels. This not only increases the efficiency of the panels, but the collected heat can also be put to use elsewhere in the building for space heating if required.

The Illawarra Flame, the University of Wollongong's winning entry in the 2013 Solar Decathlon, is also situated nearby on campus. It is fitted with both conventional PV and BIPVT and is also connected via the SBRCs electricity distributions system, providing additional generating capacity to the precinct on top of that provided by the SBRC.

### 3.4.4 Description of Building Systems

#### *3.4.4.1 HVAC*

The HVAC system at the SBRC is able to operate in three modes – natural ventilation, heating, or cooling. Natural ventilation is implemented through the use of automated windows and louvres on the building envelope. It is designed to be the primary space conditioning mode for maintaining the building within 20°C and 24°C. Outside of this comfort band, mechanical heating and cooling modes are used. The main mechanical plant equipment are as follows;

- One air cooled heat pump;
- Two water-cooled heat pumps;
- Six variable speed water pumps;
- One ground loop header pump;
- Supply and return water temperature sensors;
- Eighteen motorized flow diverting or control valves;

Ground-source heat exchange loops are used to exchange heat with the stable temperature of the ground. A variable speed water pump is fitted to the ground loop to maintain constant pressure to the system.

Operation preference is given to the Ground Source Heat Pumps (GSHP) as they are generally more efficient over the air source heat pump (which is used only to meet peak loads or in the event of GSHP equipment malfunction or servicing) due to its use of ground heat exchangers where the temperature is more suitable than the atmosphere for use as a heat source or sink.

#### *3.4.4.2 IT system*

Low energy Virtual Desktop Infrastructure (VDI) is used at the SBRC instead of traditional separate PC terminals. Each desk has only a display monitor, keyboard, and mouse, all powered over Ethernet connection with processing hardware located off site in a concentrated server configuration. A thin-client VDI terminal consumes around 8-20 W of energy compared to an average of 150 W for a traditional PC [77]. A VoIP phone system is used in place of traditional phone systems, further cutting down on energy use.

#### *3.4.4.3 Lighting*

Low energy lighting systems are used at the SBRC with occupancy sensors and daylight harvesting strategies implemented. Lights only operate once occupants are sensed or if a manual input is received from a lighting control panel. Lights remain on for a programmed amount of time after sensed occupancy ceases. Photoelectric sensors control lighting fixture output according to natural lighting levels in the zone.

The lighting system is designed to reduce general ambient lighting intensity in favour of more concentrated task-based lighting. Main office spaces may be lit to a lower level than that of a more conventionally lit office, however more focussed task lighting makes up for this at work surfaces. This reduces the amount of wasted light by supplying it only where needed.

### 3.4.5 Energy monitoring

A number of energy monitoring systems are employed at the SBRC:

*Building Management System*

The Tridium Niagara Building Management System monitors and records a number of electrical meters in the building at 15-minute time intervals. This data is logged and can be accessed at any time from the BMS server. Some meters of note are:

- Main Supply

- PV North array
- PV South array
- Mechanical services
- BIPVT

Remaining meters measure the plug, lighting, and IT loads which are separated into ground floor, first floor, laboratory, and high bay zones.

Meters are also placed on individual items of HVAC equipment such as heat pumps, fans, and water pumps. Provision is also made for future installations such as wind turbines, electric vehicle charging stations, and other experimental distributed generation. These meters are capable of measuring active, reactive, and apparent power, as well as the current, voltage and frequency of all phases and some power quality parameters such as total harmonic distortion and power factor.

#### *Solar-Log*

Additional metering of the solar arrays is possible through the online monitoring services provided by the solar installer. Energy production is logged at 5-minute intervals and can be broken up into contributions from the north and south arrays. Monthly and yearly summaries are also prepared automatically. In addition to energy production, the condition of the inverters can also be assessed through this service with the temperature and efficiencies of each inverter being logged. Inverter input voltage is also measured.

#### *Portable IEQ and PQ meters*

Where more in-depth metering capabilities may be needed, or if metering is not available on a specific component, portable power quality meters are also available to connect to the SBRC circuits on a rotational basis. These are capable of providing high resolution, detailed data and can be interfaced in a variety of ways including LAN for remote meter reading.

## 3.5 Transformational Technical Training Building – TAFE NSW

The TTT building, shown in Figure 3-12, is located at the Yallah campus of TAFE NSW was built as part of the joint funding initiative which also funded construction of the SBRC. The TTT building is designed as a net zero energy and water building and aims to achieve Living Building Challenge certification much like the SBRC. The building is used for educational, training, and demonstration purposes by the TAFE Illawarra Institute, as well as the surrounding civic and business communities.

Figure 3-12 Transformational Technical Training (TTT) building.

The TTT building is a 1,020 $m^2$ facility featuring 500 $m^2$ of teaching space including 185 $m^2$ of practical laboratory training space on the 800 $m^2$ first floor. 100 $m^2$ of administration office space and reception is located on the ground floor.

### 3.5.1 Building façade

Much like the SBRC building, a high level of insulation is present at the TTT building. Block-type wall construction is used on the ground floor where the building is cut into the slope of the ground. Steel framed external walls, clad in fibre cement panels are used on the first floor. Minimum R2.5 insulation is used in external walls.

External windows and glazed doors consist of a combination of double glazing and high performance single glazing.

### 3.5.2 Energy efficiency

As a net zero energy building, a number of energy efficient design features are present. Large north-facing windows with high performance glazing are used to maximise the amount of natural lighting. Artificial lighting is all LED and is controlled by occupancy sensors.

The building is north facing and has large roof overhangs to reduce summer solar heat gains but allow winter solar gains into the building. A solar hot water system is installed, significantly reducing loads associated with DHW heating.

### 3.5.3 Local generation

A solar PV system is installed with capacity of 28 $kW_p$. Approximately 40 MWh of energy is generated annually.

### 3.5.4 Description of Building Systems

HVAC services include a 60 kW GSHP system supplying heating and cooling to teaching spaces on the first floor. The common area and horticulture labs on that floor are both naturally ventilated. On the ground floor, a separate conventional ASHP system services the office and reception areas. Refer to water and air schematics of TTT in Figure 3-13 and Figure 3-14, respectively.

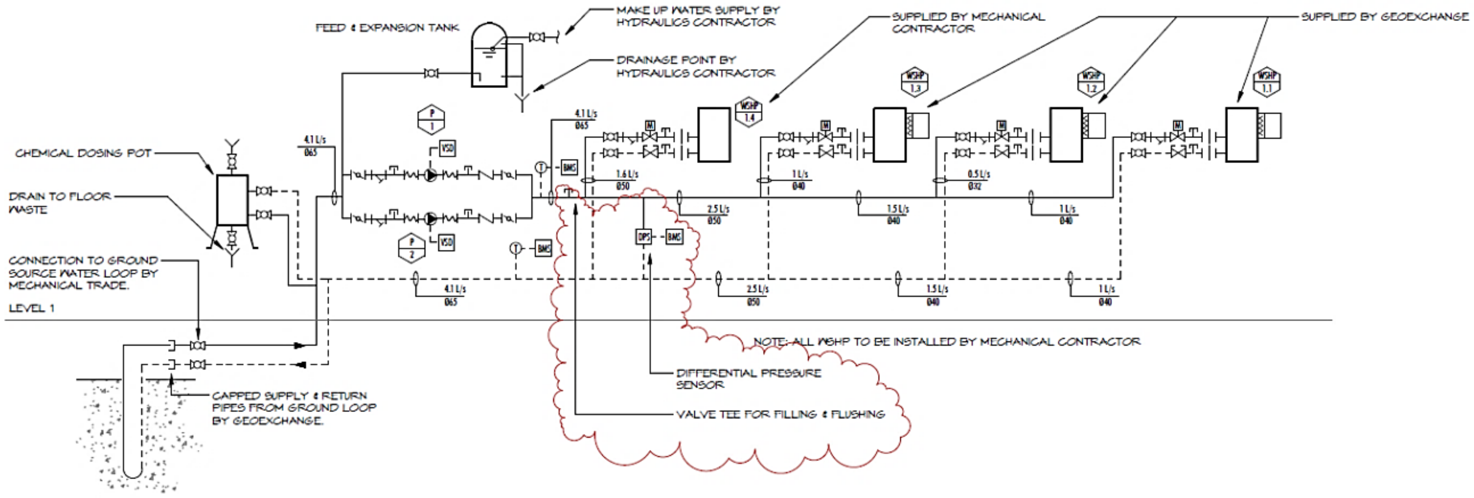


Figure 3-13 TTT building HVAC water services schematic [78].

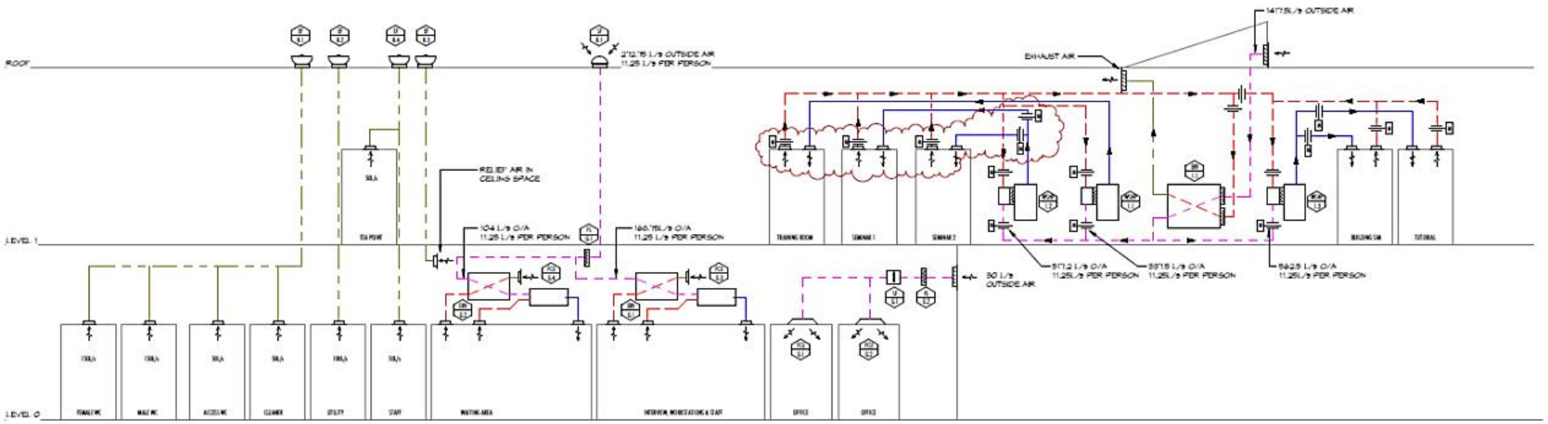


Figure 3-14 TTT building HVAC air services schematic [78].

### 3.5.5 Energy monitoring

Energy monitoring is capable through the Delta Controls BMS. Sub metering is available for electrical circuits as outlined below in Figure 3-15 using EP&T G3 intelligent meters connected to the BMS.

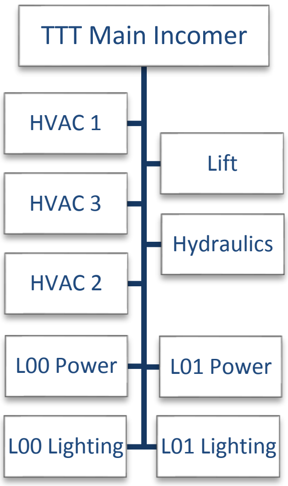


Figure 3-15 TTT electrical meters and sub-meters.

The 'Hydraulics' meter includes all energy involved with pumping and treating of the rainwater supply, as well as pumping of ground heat exchanger fluid for the GSHP system.

## 3.6 Enterprise 1 – University of Wollongong

Enterprise 1, another building situated at the University of Wollongong's Innovation Campus, is a commercial office building whose tenants include multinational corporations and UOW research institutes. It is a three-story building with a total floor size of around 10,000 $m^2$ and was opened in 2011.

### 3.6.1 Building façade

The building consists of a concrete framed shell with lightweight curtain wall cladding. Operable slatted timber louvres (shown in Figure 3-16) provide shade at the east and west ends when needed. External windows are double glazed with aluminium frames. The insulation installed in the external cladded walls achieves an R-value of 2.5.

Figure 3-16 Enterprise 1 building east/west timber louvres [79].

### 3.6.2 Energy efficiency

The building has been designed to achieve a minimum 5 star NABERS base-building rating. A base-building rating concerns the greenhouse gas emissions associated with energy consumed by core building services such as common area lighting, lifts, HVAC central plant (not including supplementary HVAC used by tenants), and exterior lighting. The base building assessment does not consider energy consumed by tenancy activities.

The 5-star base-building rating means the building can be considered as state-of-the-art for a building of its type and one which is a good candidate to be compared against net zero energy buildings. Occupancy controls on office lighting systems aim to reduce unnecessary lighting use, as well as in bathroom areas where lights are switched off after a 1 hour period with no detection. Low energy compact fluorescent downlights are used, along with T5 linear fluorescent fittings in offices. This gives a resulting overall lighting power density of 9.4 W/m$^2$, which can be calculated from electrical plans and equipment schedules in the operation and maintenance manuals for the building

### 3.6.3 Description of building systems

Mechanical HVAC equipment installed in the Enterprise 1 building includes 2 x 600 kW chillers. These are designed so that either of the two chillers is able to provide 50% of maximum demand. 2 x 202 kW gas fired boilers are installed to meet heating demand. All of the 13 Air Handling Units (AHU's) are equipped with variable speed drives. The measured total yearly HVAC energy consumption of the building for 2014 was approximately 373,000 kWh.

The lighting system as previously described is metered in combination with general plug loads. The combined yearly energy consumption of light and power was approximately 1,082 MWh. It was estimated that the contribution of lighting to this combined load is 492 MWh, based on the model developed for this research which uses lighting specification inputs described above. Two lifts operate between the three above-ground floors and the basement carpark. These contribute around 8,000 kWh per year to overall energy consumption.

### 3.6.4 Energy monitoring

Less data is available for the building loads in Enterprise 1 as this is a much more conventional building and metering is less extensive. However, due to the NABERs rating requirement, electrical, gas, and water metering is required for key building systems so that consumption of these sources can be factored in the annual NABERS assessment. The electrical meters of interest in this study are:

- Incoming mains
- 3 HVAC meters measuring water pumps, cooling towers, pumps, chillers, AHU's, and other ventilation fans
- Base-building light and power
- Tenant light and power

## 3.7 Summary of building features

A brief summary of the key building features for all case study buildings is given in Table 3-1. These features may have a significant bearing on the overall energy performance of the building and the benchmark model for each case study will be constructed around these features.

Table 3-1 Summary of building features

| | TTT | SBRC | Enterprise 1 |
|---|---|---|---|
| **Occupancy Type** | Education and Training | Education, Research and Training | Commercial |
| **Approx Number of Occupants** | 150 | 50 | 900 |
| **Number of Floors** | 1 | 2 | 4 |
| **Total Floor Area** | 1 021 | 2 600 | 11 874 |
| **Wall Type** | Combination of concrete blockwork and metal clad/steel frame | Combination of concrete and steel framing, with recycled brick and timber cladding facade | Concrete with curtain wall cladding |
| **Wall Area** | 813 | 2 261 | 3 730 |
| **Glazing Type** | Combination of double glazing and high-performance single glazing | Double glazing | Double glazing |
| **Glazing Area** | 218 | 652 | 2 261 |
| **Lighting Type** | LED | LED | T5 Fluorescent T-Bar Troffer in office spaces |
| **Lighting Control** | Motion sensor & PE cell | Motion sensor & PE cell | Control schedule and motion detection after hours |
| **Average Lighting Level** | 193 | 213 | 320 |
| **Lighting Power Density** | 4.75 | 1.60 | 9.40 |
| **HVAC Type** | 3x Reverse cycle geothermal heat pumps (total cooling capacity 45 kW)<br>1x water-cooled VRF-type heat pump (total cooling capacity 27 kW) | 1x Air-cooled reverse cycle chiller (total cooling capacity 110 kW)<br>2x Reverse cycle geothermal heat pumps (total cooling capacity 34 kW) | Central chilled water system (total cooling capacity 1200 kW)<br>Central gas-fired hot water system (total heating capacity 400 kW) |
| **Cooling Setpoint** | 24.5 | 24.5 | 24.0 |
| **Heating Setpoint** | 19.5 | 19.5 | 21.0 |

## 3.8 Summary

In this chapter, the purpose and methodology for simulation of the case study buildings has been presented, as well as details on the buildings themselves. The uncertainties that may cloud simulation results such as unpredictable weather conditions and occupant behaviour were considered and a validation methodology was presented to account for these uncertainties.

The schedule and methodology of simulations was outlined for glazing, lighting control, window shading, and HVAC setpoint. Case study buildings to be simulated were introduced with a description of their construction and features, including energy efficient building technology and energy monitoring equipment that may be installed.

# Chapter 4 Model Validation & Performance Simulation

## 4.1 Purpose of building simulation

The work in this chapter focusses on modelling and simulation of energy consumption related to different building scenarios for the three test cases introduced in Chapter 3. Through simulation, it is possible to investigate the impact on energy consumption caused by utilising different construction materials, appliances, lighting systems, etc. in the building design as well as how occupants interact with a building which might otherwise be impractical or impossible to investigate in reality. Verification of the three case study building models is an essential step towards having confidence in the results of the simulations performed in the next chapter. The outcomes of these simulations will demonstrate the effects on whole-building energy consumption that different building elements or parameters may have had and how this may impact the future design of net zero energy buildings.

### 4.1.1 Relevance to net zero energy

When considering net zero energy building principles, reduction of energy requirements is at the forefront of objectives. Simulating different building technologies, operating parameters and usage schedules enable a designer to optimise the design of a building to use the least amount of energy possible, reducing the capacity or operation time of renewable energy required to achieve net zero.

In such a complex system as a building, altering one parameter to achieve a positive outcome in one aspect may have a detrimental effect on other aspects. One example of this is to introduce a window shading solution such as blinds or curtains. In summer, shading the windows during the day likely diminishes the effect of solar gains on the building, potentially lowering the cooling load and hence the electricity required by the HVAC system. However, a consequence of covering windows during the day is that the amount of daylighting is reduced, therefore requiring an increase in interior artificial lighting and hence an increase in the electricity required to light the building to a comfortable level. To complicate matters further, whilst the HVAC loads are reduced by implementing window shading, the increase in artificial lighting required as a result generates heat and potentially increases HVAC loads in some situations.

Building modelling and simulation provides a way of quantifying the effects of such interdependent systems. In the above case, simulation would enable the designer to decide whether or not window shading would be the most effective approach to improving energy efficiency, or whether the added lighting energy required and the potential cooling load increase from waste heat has a negative impact on the overall energy consumption of the building.

In this project, several interdependent scenarios similar to the example above will be investigated using building simulation. DesignBuilder [80] is chosen for this given that it is readily available, user friendly, and crucially, provides a demonstrable level of accuracy. It is necessary to determine the sensitivity of the building to changes such as type of window shading, lighting, HVAC system, and construction materials used, as well as the way in which the various technologies are implemented. The aim of simulating these scenarios is to minimise the overall building energy consumption with a view to achieving net zero energy status when all factors of the different building systems are considered, as well as to determine the contribution that energy efficient technology may make to overall energy savings to a building in a broader sense.

## 4.2 Planned outcomes of simulations

The application of the simulation methodology described in Section 3.3 was planned for implementation to each of the three test cases. The planned outcomes of the simulations were as follows (noting that it was anticipated that the outcomes would have relevance beyond the case study buildings, i.e. would be applicable to efficiency improvements in the built environment in general):

- Gain an understanding through simulation of how different building elements interact through a variety of scenarios and what consequences this interaction may mean for whole-building energy intensity in a broader context;
- Make comparisons between benchmark and simulated scenario data to determine the overall contribution to energy savings that each energy efficient technology makes;

- Enable discussion on the potential for improvement of current building codes and operating procedures concerning the energy efficiency of building components.

## 4.3 Background of models

The case study buildings include two net zero energy buildings and one modern commercial building. The two net zero buildings are small educational facilities – one approximately 1,000 $m^2$ and the other approximately 3,000 $m^2$. The commercial building is approximately 10,000 $m^2$.

Despite the differences in purpose and size between the net zero educational buildings and the commercial building, meaningful conclusions were expected to be drawn from the comparisons made between simulation results for the three buildings.

### 4.3.1 TTT

The DesignBuilder model of the Transformation Technical Training (TTT) building at TAFE Illawarra's Yallah Campus in NSW, Australia, was developed using architectural, mechanical, and electrical drawings sourced from the project manager of the building construction. The building floor plan was modelled as specified in the drawings, as were all glazing elements and lighting specifications. Some simplifications were made to the model where deemed either too complicated to model, or would have had little bearing on the simulation results, such as the finer details of the roof design in some areas.

As the DesignBuilder library has an extensive, but not exhaustive library of building materials, good approximations were found for wall, roof, and floor construction materials, as well as insulation and window glass. A visualisation of the TTT building model developed in DesignBuilder is provided in Figure 4-1, illustrating the external layout of the building.

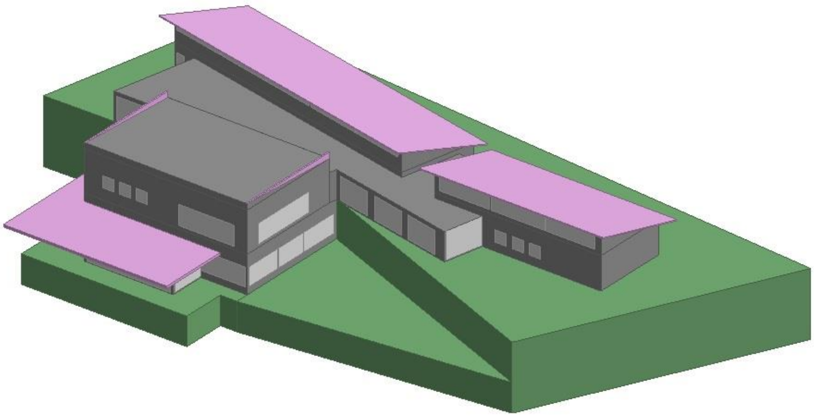

Figure 4-1 TTT building model physical geometry as modelled in DesignBuilder.

The lighting specifications and the required lighting intensity levels for each building zone were included in the provided design details, so it was relatively straightforward to enter this data into the model to provide the specific lighting output. The design level of lighting output was adjusted to suit the DesignBuilder requirement of specifying lighting units in $W/m^2/100$ lx. Using these units allows for variation between the different case study buildings. Each building has varying lighting requirements and comparing them on a lighting power density basis alone would not provide a fair comparison. Introducing the lux levels in the lighting specification allows for fair comparison between buildings.

For example, Building 1 has an installed lighting power density of 5 $W/m^2$ and is required to achieve an overall lighting level of 100 lx. This results in a lighting specification of 5 $W/m^2/100$ lux. Building 2 has a lux level of 240 and a lighting power density of 6.5 $W/m^2$. The lighting specification for Building 2 is 2.71 $W/m^2/100$lx. It is illustrated that although the lighting power density in Building 2 is higher than that of Building 1, the lux level required is also higher. Building 2 is more efficient at achieving its required lux level than Building 1.

As lighting in the building is controlled primarily by zone occupancy, lighting operation schedules were assumed to closely align with building occupancy schedules. These were both approximated based on the energy use data, which tends to be indicative of building occupancy and occupant behaviour to some degree, and were also correlated with anecdotal evidence from staff occupying the building of general occupancy periods. Additionally, daylight lighting control was used to adjust the output depending on the amount of natural light entering the room.

The HVAC system was modelled using the *Simple* mode in DesignBuilder. This reduces the complexity of the model by eliminating the requirement to specify every element of the HVAC system – a complex and intensive process. Instead, *Simple* mode uses an idealised load calculation method which utilises constant coefficients of performance as specified by the modeller [80]. It is possible to specify the energy associated with pumps and fans separately which can be determined using BMS energy data. Because *Simple* mode is used, the energy model for HVAC is not expected to be as accurate as other aspects of the model when compared to the real building, however relative changes in energy use should still be valid across model results since the HVAC model specification will be consistent.

The natural ventilation mode during simulation was *Scheduled* as opposed to the more complex alternative of allowing DesignBuilder to determine through calculation (i.e. *Calculated* mode). *Scheduled* sets a nominal air flow rate for the zone and is controlled by an operation schedule. Natural ventilation can occur if zone temperatures and outside temperatures are within the prescribed temperature bands and as long as the schedule allows. This is different to the *Calculated* mode which, instead of using a nominally specified air flow rate, calculates the flow rate based on outside conditions such as wind direction and velocity, and window design. As sufficient results were achieved using scheduled natural ventilation, *Calculated* mode was not necessary and further model simplification was achieved.

Air infiltration was left at the default constant value of 0.7 air changes per hour (ac/h) as specified by the standard DesignBuilder modelling template. This value was left at the default as no measured data from air permeability tests was available to better inform the model. It was assumed that air infiltration was constant at all times due to it being infeasible to test for this. A constant infiltration rate was assumed across all three buildings being studied.

As little data was available about electrical equipment in the building, assumptions had to be made based on the small amount of energy data which was available. This energy data included HVAC loads, lighting loads, and general purpose outlet (GPO) loads for the first three months of 2015; two summer months and the first month of autumn. Generic loads were then specified in the model with the intention to represent all general electrical equipment such as computers, desk lamps, kitchen appliances, etc.

Once all model input requirements had been satisfied, many simulations were run in order to fine-tune the benchmark model against the available measured data. This was to ensure a properly validated starting point. It was found that much of the uncertainty of the model came from approximations of operation and occupancy schedules. Using the available data, it was possible to tune much of this uncertainty out during the validation simulations. Some uncertainty remained as stochastic factors such as occupant behaviour and weather events will always ensure some degree of uncertainty.

### 4.3.2 SBRC

The Sustainable Buildings Research Centre (SBRC) model was based on one developed previously by another researcher [51]. As this model was developed for different purposes, its physical accuracy was not as high as the TTT model and some adjustments were required to get the model representative of the physical building. Glazing specifications were not according to the architectural drawings, and other elements such as skillion roof overhangs were not accurate. Some simplifications were also made such as the omission of exterior balustrades and stairways, and complex slatted sunshades at the east and west of the building. The geometry of the SBRC model from DesignBuilder is illustrated in Figure 4-2.

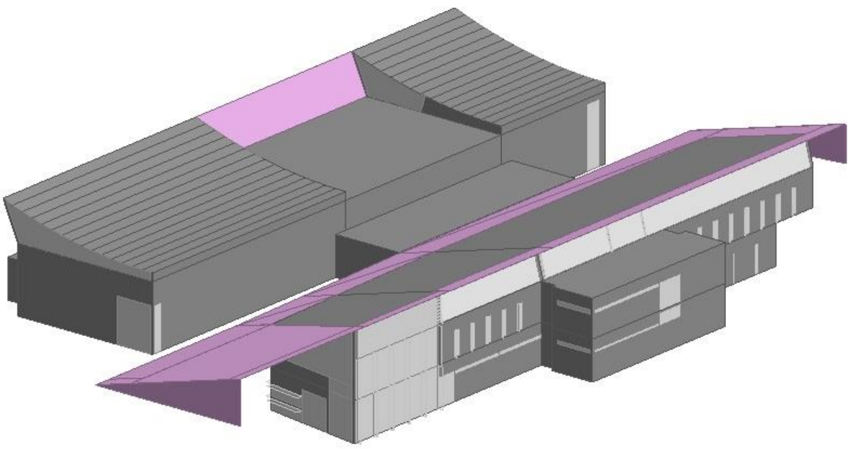

Figure 4-2 SBRC building model physical geometry as modelled in DesignBuilder.

Once again, knowing the lighting specifications and the required lighting intensity levels for each building zone, data was entered into the model to provide the specific lighting output. The design level of lighting output was adjusted to suit the DesignBuilder requirement of specifying lighting units in $W/m^2$ per unit 100 lx.

Lighting schedules were determined from BMS lighting energy use data. It was possible to develop a schedule to follow the underlying trends present in the energy data for the interior and exterior lighting of the building. Lighting daylight control during the day is also used to adjust the output depending on the amount of natural light entering the room.

Like the TTT, the HVAC system for the SBRC was modelled using the *Simple* mode in DesignBuilder. Energy associated with pumps and fans is specified separately and is informed from viewing BMS energy data.

The natural ventilation mode used was '*Scheduled*'. Air infiltration was applied building-wide at 0.3 ac/h in accordance with the targeted infiltration rate being less than 0.5 as specified in the SBRC building users guide. It was assumed that air infiltration was constant at all times.

Generic loads in the model were specified based on BMS electrical data. These are intended to represent all general electrical equipment such as computers, desk lamps, kitchen appliances etc.

As with the TTT building model, benchmarking simulations were performed in order to establish model validation against measured data. Uncertainties associated with operation schedules were eliminated as much as possible, and window shading detail was added to cut down on solar gains into the building which appeared to give unrepresentative temperature results due to the large glazed curtain walls on the western end.

### 4.3.3 Enterprise 1

The Enterprise 1 model was built from scratch using the architectural drawings. The building façade has been simplified due to the high number of windows resulting in an unacceptable simulation time. The total window area however has been accurately represented. Glazing type for the model was specified as double glazed clear. Figure 4-3 shows the model geometry of the Enterprise 1 building model.

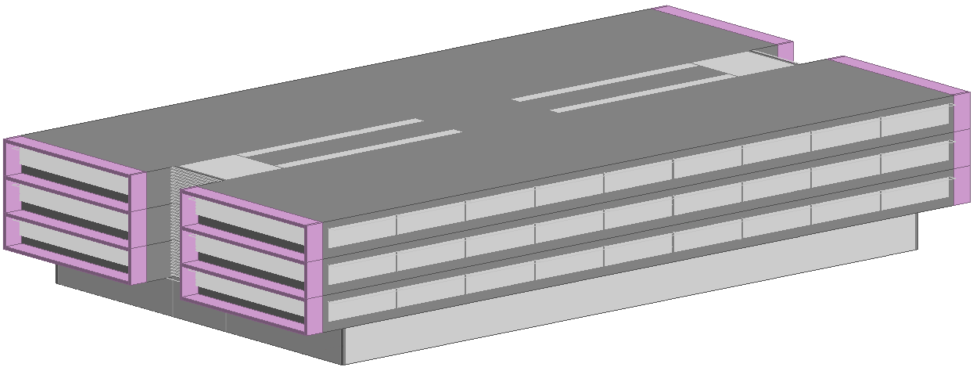

Figure 4-3 Enterprise 1 model physical geometry as modelled in DesignBuilder.

The air infiltration rate assumed for the Enterprise 1 model is 0.7 ac/h, and this is assumed to be constant at all times. Simple HVAC mode is used here to reduce modelling complexity, with the auxiliary loads being specified separately, just as they are done with the other two models.

Lighting densities for the model were specified according to those outlined in the Enterprise 1 building construction documentation. An average base lighting power density of 9.4 W/m$^2$ was calculated based on the primarily 28 W T5 fluorescent lighting fixtures installed throughout the majority of spaces in the building.

### 4.3.4 Summary

With the models being created to the highest level of accuracy according to the details available, there are still unknowns and assumptions made which may affect the behaviour and results of the models. To reduce errors associated with these assumptions, it is necessary to perform a validation process for each of the models to ensure they will give reliable and representative results.

## 4.4 Validation of models

To ensure that building models are an accurate representation of reality and that their data outputs are reliable, it is critical that they are properly validated and verified so that they can be relied on to give useful conclusions about net zero energy buildings. By comparing the data generated by the models with analogous data measured from the real buildings, and coupling this with a weather file in the model created from actual measured data from a site nearby to the building, errors in the model can be identified and tuned out to a point where the building model can be said to be a satisfactory representation of the real building. Errors associated with random events and behaviours in the building must be identified and discounted during the validation process. It is very difficult for the model to be able to consider these random events and thus care should be taken to ensure they do not influence the validation process. This may result in the building being tuned for the specific behaviour observed during the validation time period, but then the model would cease being properly representative outside of the validation period. The desired result is a model that can represent the building over any given year with reasonable accuracy.

### 4.4.1 TTT

The data available for validating the TTT building model was limited. Whilst the TTT BMS has the capabilities of storing large amounts of energy and temperature data, a BMS computer failure had resulted in a malfunction with data being written to storage. As a result, energy meter data was only available for the first three months of 2015, covering a seasonal transition period of summer to autumn. Temperature data from the BMS was also unavailable. This challenge was overcome by using data sourced from iButton temperature sensors installed at the TTT as part of research being carried out by another researcher from the SBRC. This data, combined with a weather file assembled using a combination of data measured at the TTT and also from the SBRC weather station (about 20 km north of the TTT), enabled the thermal response of the model to be validated against measured data – albeit for only a winter heating case between 20/7/15 and 27/7/15. As outlined in Section 3.2.2, ideally temperature data for both summer cooling, winter heating, and natural ventilation would be used to be able to ensure comprehensive validation. However, in this case the data simply did not exist to be able to make this possible, and waiting for summer in order to capture the data was unfeasible due to time constraints. Nonetheless, a good result was observed when the temperature profiles of the model were compared with those of the measured data in the selected rooms of the building. The rooms chosen for validation were selected for their positioning in the building and their types of use. This is summarised in Table 4-1.

Table 4-1 TTT representative zones for temperature validation.

| Room | Reason for selection | Position in building |
|---|---|---|
| **Ground floor office** | Representative of the ground floor of the TTT in both type of use, and intype of climatic conditions | Ground floor – SE side |
| **Seminar** | Typical classroom on northern side of the building with high levels of solar gain | Level 1 – NW side |
| **Building simulation room** | Classroom and large meeting room. Chosen in addition to the Seminar room due to being in different location and experiencing lower solar gains | Level 1 – SE side |
| **Gallery** | Large common area. Naturally ventilated only. All other rooms chosen for validation have heating and cooling available | Level 1 – Spanning E-W |

The period chosen for validation of temperature profiles was 20/7/15 to 27/7/15. This was chosen primarily because it was the week with the most complete weather dataset and temperature data, however it is also a good representation of a typical Winter operating week at the TTT. Figure 4-4 shows the comparison between measured temperature and simulated temperature for the ground floor office. A sound match is observed between the two profiles. The model appears to overestimate the peak temperatures of the room over the two weekend days when no HVAC is operating in the space.

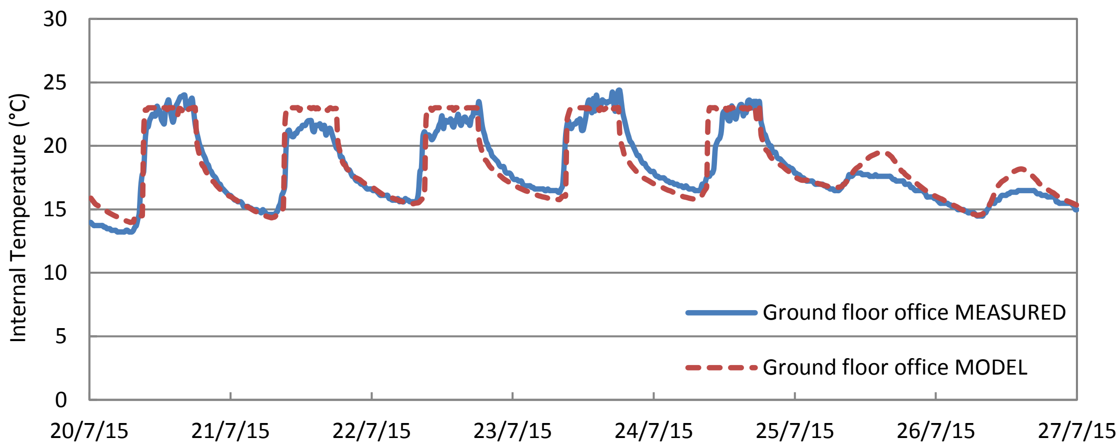


Figure 4-4 TTT Ground floor office temperature profile comparison.

The NMBE is calculated as -1.1%. The negative sign indicates that the model over predicts the temperature on average, and by a magnitude of 1.1%. The highest levels of error are observed to be in the mornings where HVAC does not commence operating at the exact same times in reality as in the model. Error during this stage of the day can be more readily discounted as the factors influencing it (variations in occupancy-driven

HVAC operation) are difficult to predict and thus build into the model. This error can be reduced by matching simulation schedules to occupancy data; however, this would greatly increase modelling time and complexity, and could never be robust enough to exactly match energy/temperature profiles in all situations. Finding an exact match of energy/temperature profiles is not the intention here, rather finding a model that is able to represent the real building in general terms, without considering the randomness associated with buildings such as the weather and human factors, is the main aim. The most important sections of Figure 4-4 are how the building cools down at the end of the day once occupancy has ceased and artificial heating has ended. As can be seen, the model behaviour compares well to that of the real building during these periods. Having plotted the model values and measured values on a scatter graph, the coefficient of determination can give an indication of how well the model fits the measured data. This is shown below in Figure 4-5.

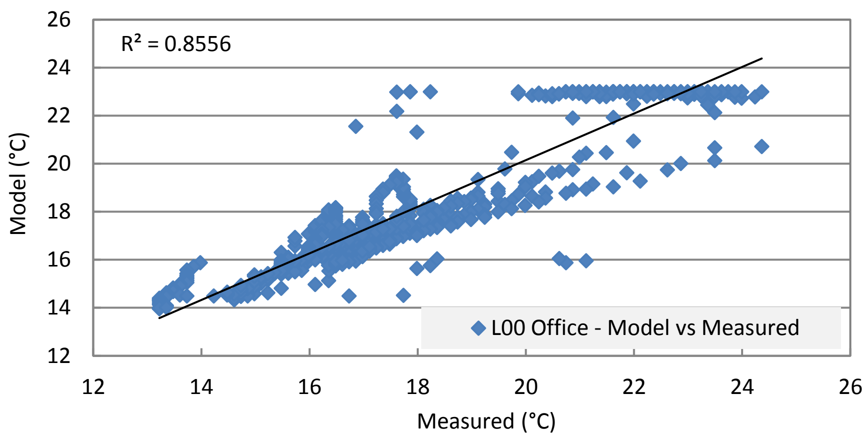


Figure 4-5 $R^2$ for ground floor office temperature comparison.

A good correlation is observed showing an $R^2$ value of 0.8556 meaning 85.6% of variance is explained by the model. The horizontal streak of off-trend data points on the upper right hand side are due to the model heating the building in an ideal manner such that the temperature in the zone is held at exactly the heating setpoint. This would not be true of the real building which is permitted to vary within the comfort band and in some cases heating is not present at all in the real building over the sample validation period.

Figure 4-6 shows the results of the same comparison for the seminar room at the north western area of the first floor. Again, a sound visual comparison is observed. The

NMBE in this case is -0.5%; a close match, with the model on average slightly overpredicting temperatures.

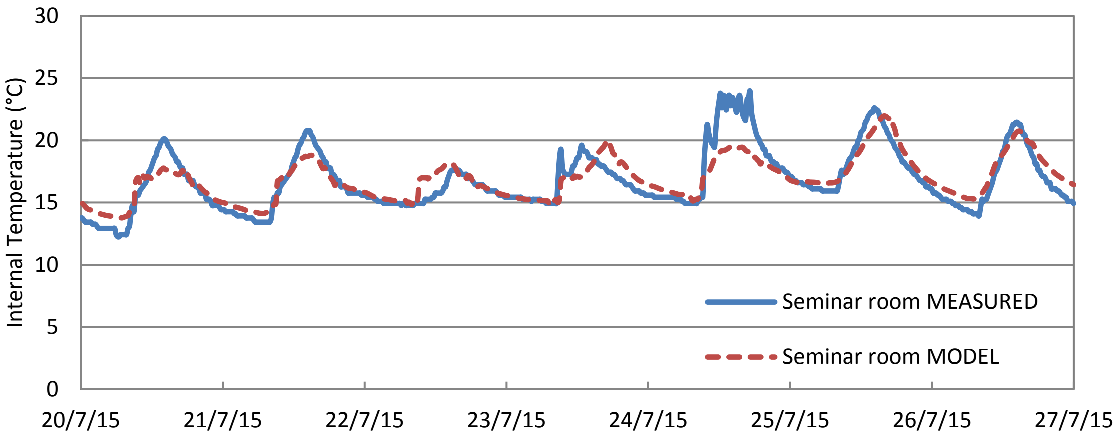


Figure 4-6 TTT Seminar room temperature profile comparison.

As in the gound floor office case, the building model responds very well during the unoccupied ‘cooling down’ overnight period,  indicating that the thermal response of the building model is sufficiently accurate. Observable differences once again appear to come from the model’s inability to predict random HVAC activity which deviates from the general schedule. The temperature profiles for the two weekend days show a good match, with minor notable differences being a slight delay in the temperature peak of the model on Saturday 25/7/15 and the model taking longer to cool down overnight on both days.

The temperature profile comparison for the building simulation room is shown in Figure 4-7. Here the match is not as good as those seen previously, however a broad correlation is still observed. The NMBE is -7.6%. Whilst this error is higher than those seen previously, it is still well within the acceptable 15% limit specified in Section 3.2.2, and general behaviour of the model remains reasonably consistent with actual.

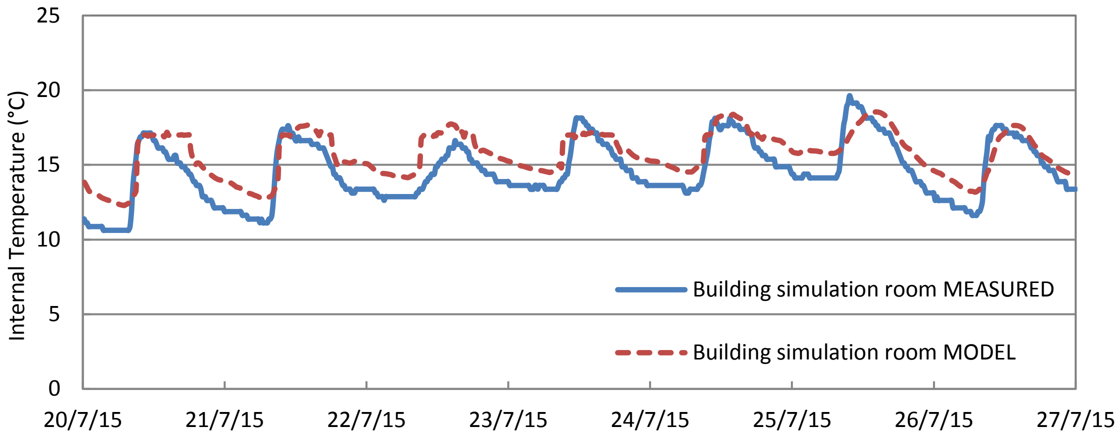


Figure 4-7 TTT Building simulation room temperature profile comparison.

Figure 4-8 shows the scatter graph calculating the coefficient of determination. An $R^2$ value of 82.6% shows good correlation between the model prediction and the measured data.

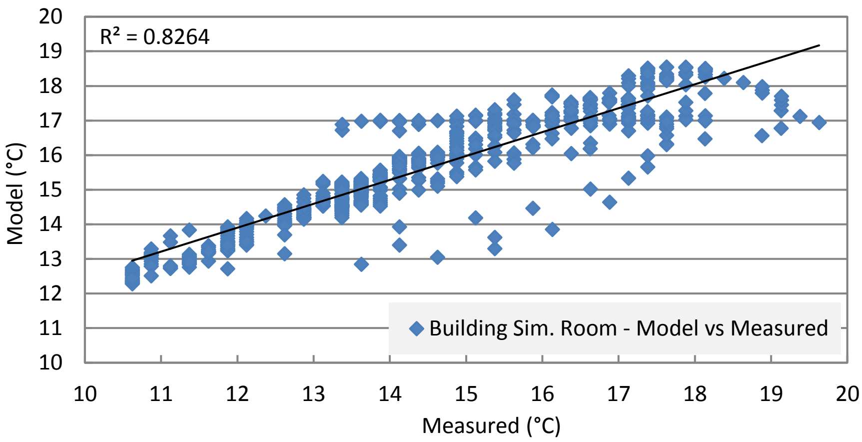


Figure 4-8 $R^2$ for building simulation room temperature comparison.

The model in this case appears to overestimate the temperature during overnight periods. This is the area where previous comparisons have performed best. However, taking a look at the comparison for the Sunday 26/7/15, the comparison is much better than the previous weekdays. It may be possible that the poorer comparison during the week was due to occupancy factors involving the HVAC system. It appears as though the heating was activated in the mornings on Monday and Tuesday, but that this heating was not sustained throughout the day. The building then started cooling from an earlier time than that of the model. The similar (but offset) cooling gradient most notably on the Monday certainly suggests that this may have been the case. As this room is used for larger meetings, sometimes involving important guests, the facilities manager tends to intervene in the HVAC settings occasionally. This may help to at least partly explain what appears to be an erratic temperature profile for this room, leading to discrepancies with the model.

Figure 4-9 shows the comparison for the gallery. As this zone is natural ventilation only, it is representative of the rest of the building when it operates under mixed-mode natural ventilation conditions as it often would during autumn and spring periods. It is therefore important that this comparison be a good match in order to give confidence in the overall building mode performance whilst in natural ventilation mode. A generally favourable comparison is observed with a NMBE of -10.07%. This is the highest error of all building zones examined, but still within the 15% limit.

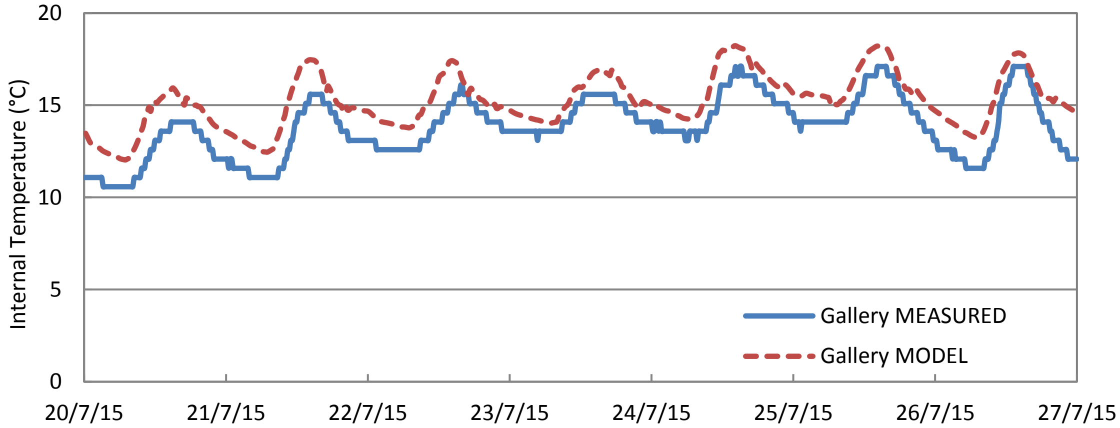


Figure 4-9 TTT gallery temperature profile comparison.

The model performs well in following the correct trends throughout the period, although it does overestimate the temperature in the gallery by 1-2 °C in parts.

It should be noted that some of the automatically actuated horizontal external louvers installed on the western side of the gallery have been stuck in the open position for an extended period of time due to equipment failure. It would be difficult to quantify the effect that this would have on the internal temperature of the space, although it must be assumed that this would go some way to explaining the overestimation of the temperature in the model.

Overall, the temperature profiles generated by the model compare well with those measured in the building. As mentioned above, a common discrepancy was that the model tended to overestimate the temperature to a minor degree. A possible reason for this in the gallery is given above but this does not explain the other zones. One factor that might have some bearing on this is the solar heat gain. An assumption was made in generating the weather file for this validation that the solar insolation data at the TTT building site would be close enough to that of Wollongong. Solar data measured by the SBRC weather station was subsequently used owing to the fact that the TTT weather station data was inaccessible. A smaller than assumed solar heat gain into the building would certainly explain some of the difference in temperature. Many other factors may also contribute. The physical model of the building is a simplified representation. Not all walls, internal and external, are exactly as constructed in reality. Assumed insulation performance specifications are used in the model which may not match those of the real building exactly. Occupancy also may play a role. As this is an educational building, occupancy rates fluctuate throughout the year and are difficult to both predict and survey at times. The modeller must make a reasonable assumption in regard to this. Follow-on effects from occupancy which are difficult to account for in the model, such as manual window operation or HVAC setpoint adjustment may also contribute to temperature differences.

Having taken all of these contributing factors into account, the thermal performance of the model was considered a sufficiently accurate representation of the real building for it to be considered valid.

The second stage of validating the model as outlined in Section 3.2.2 was a comparison of energy use. Here, it must be noted that energy use is more sensitive to stochastic influences than temperature profiles. Whilst the temperature profiles of the building will generally follow broad patterns with minor variations as a result of occupant behaviours or other random changes in behaviour, energy use can exhibit more significant changes depending on the size of the electrical equipment and its frequency of use. Lighting loads for example are generally constant and follow a regular pattern most of the time. Higher than normal use may come from occupants working late hours or poor weather leading to reduced daylighting levels. Both of these will lead to short term increases in lighting energy consumption. The same can be said for general equipment power loads. This category includes any equipment plugged into a regular 230 V single phase general purpose outlet such as computer and office equipment, microwaves in kitchens, etc. Fluctuations in general energy use should be expected to correspond with changes in building occupancy rates, such as holiday periods.

Figure 4-10 shows the comparison of lighting electrical energy consumption at the TTT for the first three months of 2015. The data is in daily totals (kWh) as this is what was available from the limited range of data from the BMS. Each peak and trough on the chart represents a full week (consumption over the two weekend days is significantly lower than on weekdays). The NMBE is calculated as 12%, indicating that the model under predicts the lighting energy use in the building. This NMBE is slightly outside of the acceptable range as outlined by ASHRAE Guideline 14. As well as this, the calculated CVRMSE of 38% is also outside the range of acceptable error.

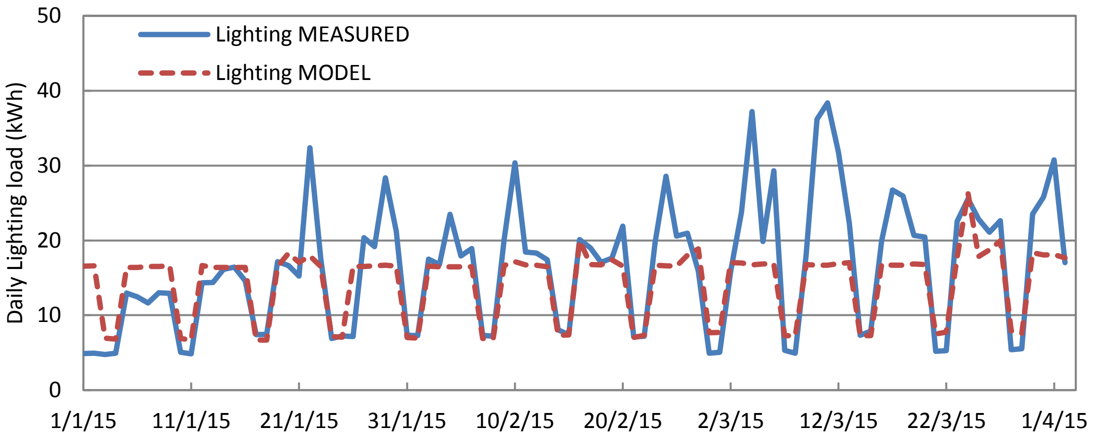


Figure 4-10 TTT lighting electrical use comparison.

It is important to note that lighting and equipment use is heavily influenced by human behaviour, a factor which is difficult for the model to predict in such an unconventional and non-commercial building. A higher sample size of data may have improved the correlation, as would higher resolution data. Visual inspection of Figure 4-10 indicates that the lighting model is generally representative of the TTT lighting system when unforeseen increases or decreases in use attributable to human behaviour are discounted. It must be noted that at the start of the graph, summer holidays are underway for the month of January and thus building occupancy is low at this time. This explains why the model is overestimating lighting use at this time. The first two weeks in March experience a large spike in lighting use which was not predicted by the model. Reasons for this could be a combination of overcast weather and the return of classes to the building for the new semester, resulting in longer occupied periods for that fortnight due to orientation proceedings.

The comparison of general equipment power loads is shown in Figure 4-11. Here, three distinct levels of general power use are observed in the BMS data. Logical speculation may explain this as follows: the first stage spanning from the start of January to the end is the summer holiday period where all students and staff are away; the second stage, which sees an increase of around 40% corresponds with the return of staff to work; and the third stage which is a further increase of around 25%, and coincides with the return of classes and student occupancy. Without a full year of data, it is difficult to make accurate enough assumptions about general power use to be able to build a model fully able to predict it. This is further complicated by the timetabling methods used to schedule classes in the building as they will vary from year to year and are somewhat sporadic due to the remoteness of the campus on which TTT is situated.

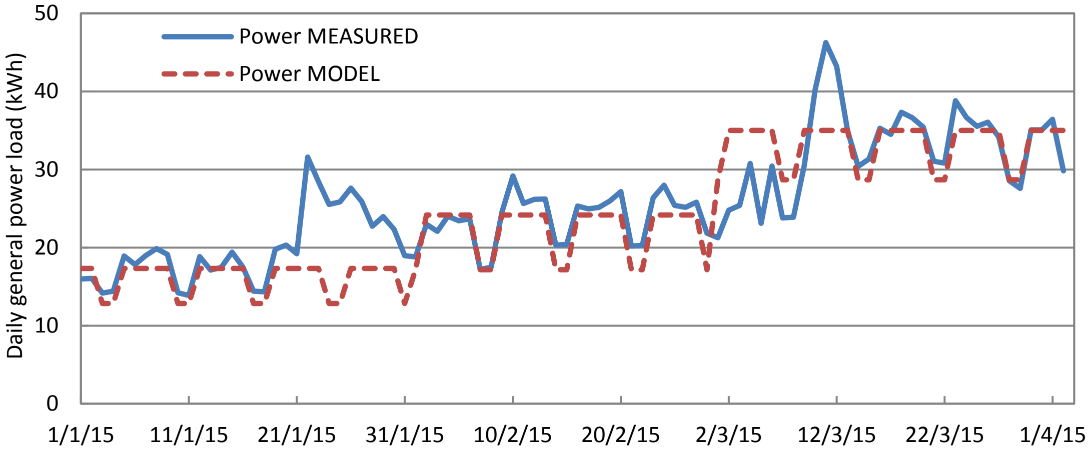


Figure 4-11 TTT equipment power electrical use comparison.

Because of these complications and unknowns, the model has been developed to best suit the data available. The NMBE for general equipment loads is 6% and the CVRMSE is 18%. While the NMBE is within acceptable limits, the CVRMSE for general power is slightly outside the 15% limit.

Whilst electrical loads may vary slightly throughout the week, the model is not detailed enough to factor in these random variations, thus distinct linear patterns are seen throughout the scatter graphs presented in this chapter, where the model output will stay relatively constant while the measured load profile experiences some variation. Again, higher resolution data for a longer period would possibly help to mitigate this effect.

An assumption is made, in lieu of the rest of the year's data, that the general power usage continues on at the same level seen at the end of the available data until the winter holidays, where it steps back down to a staff-only level. It will then step back up once classes return and then finally step down to the lowest level around December.

The HVAC model comparison is shown below in Figure 4-12. As can be seen, the model is not as successful at predicting HVAC use as it is in other respects, with a calculated NMBE of 12% and a CVRMSE of 50%. Nonetheless, the model does follow the measured patterns, and peak energy use in most cases compares well, with the exception of periods in late January and early February. The '*Simple*' HVAC model setting in DesignBuilder was used in this scenario which assumes a nominal COP for equipment and constant loads for system pumps. It is possible that with more time, a detailed model could be developed to simulate a more representative HVAC model, however detailed HVAC modelling requires a higher degree of technical proficiency and more detailed system information than was available.

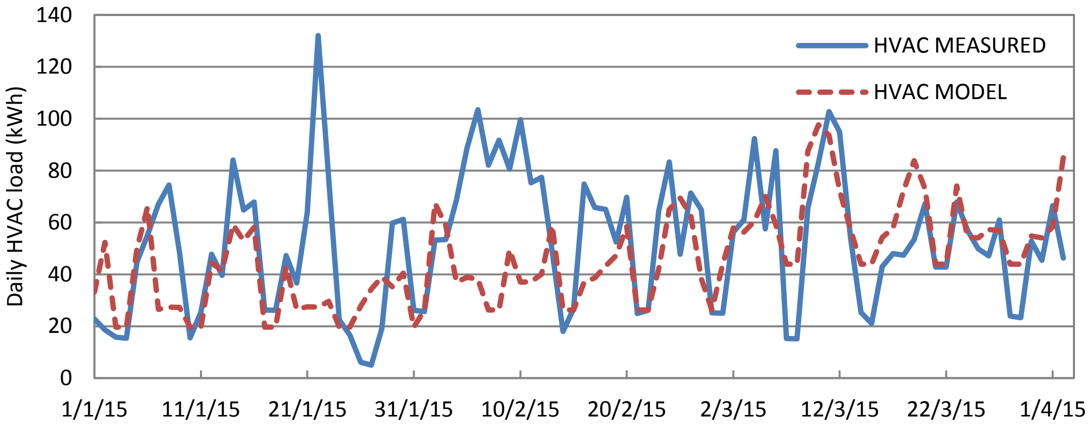


Figure 4-12 TTT HVAC electrical use comparison.

For the purposes of this study, a Simple HVAC model will be sufficient to measure the relative impacts on HVAC loads that each scenario will generate. Overall, the HVAC model exhibits the correct general behaviour, so it can be said to be moderately representative of that of the building.

Having simulated the TTT building using historical weather data and compared results to measured temperature and energy data, an assessment must be made as to whether the model is sufficiently representative of the real building. Whilst the model failed in parts to meet the acceptable limits as prescribed by ASHRAE for energy modelling, it did perform well in thermal modelling.

Much of the source of error in energy modelling can be put down to unpredictable behaviours and events for which the model has no way of factoring in. A larger building with a higher number of occupants and more regular operating hours would not be as sensitive to these issues as this building is, where anomalous events and behaviours are much more significant due to much smaller base building energy loads. With these elements considered, and given that the building thermal model behaves well, the overall building model can be considered a valid representation of the real building when stochastic influences are ignored. Other minor possible sources of error may have come from slight differences between the measured solar insolation data measured by the SBRC weather station as data measured at the TTT building was not available. However, this will not affect the final results of building modelling given that TMY weather data will be used.

### 4.4.2 SBRC

Although the SBRC has extensive data storage capabilities, commissioning issues in the first full year of the buildings' operation meant that complete energy data was not available. Fortunately, temperature data representing all three building modes was available and thus the building's thermal response could be validated more extensively than the TTT building model, where only winter heating data was available.

While energy data was also available for summer and winter periods, it was not as comprehensive as that available for the TTT building, with general equipment loads not available. HVAC and lighting load data was available for the periods of 1/1/14 to 31/3/14 (two months of summer plus one month of autumn) and 1/5/14 to 31/7/14 (one month of autumn and two months of winter).

Temperature data sourced from the BMS, combined with a weather file assembled using Bureau of Meteorology data, enabled the thermal response of the model to be validated against measured data for a summer and winter week. Three rooms of the building were chosen to be representative of the building's thermal performance in consideration of their position, the architectural elements present in the room, and their use. The rooms chosen are summarised in Table 4-2.

Table 4-2 SBRC representative zones for temperature validation.

| Room | Reason for selection | Position in building |
| --- | --- | --- |
| **Flexi lab 3 – Energy lab** | Ground floor room with small north and south facing windows. Large solar inverters are installed here, giving high waste heat output. | Ground Floor, SW side |
| **Flexi office 1 – Water lab office** | A central ground floor room on the western side with small south facing windows only. | Ground Floor, SW/central |
| **Office East** | Large open plan area with large amounts of glazing | Level 1, E side |

The periods chosen for validation of temperature profiles are outlined below in Table 4-3.

Table 4-3 SBRC model thermal validation periods.

| Season | Start Date | End Date |
| --- | --- | --- |
| **Winter** | 14/7/14 | 21/7/14 |
| **Summer** | 15/12/14 | 22/15/14 |

The following graphs show the comparison between the modelled and measured temperature profiles for the rooms chosen in Table 4-2 for the winter and summer periods. Figure 4-13 shows the temperature profile comparison for the energy lab in winter. This room is situated on the ground floor of the building and houses laboratory equipment for thermodynamics and electrical technology. It is also the location of seven solar PV inverters, six of which are large 20 kW 3-phase units. A relatively poor comparison is observed between the model and the measured data for both winter and summer periods, with summer being shown in Figure 4-14. The NMBE for the winter and summer periods are 6.8% and 8.2% respectively. This means that the model under-predicts the temperature in the energy lab by an average of 7.5%.

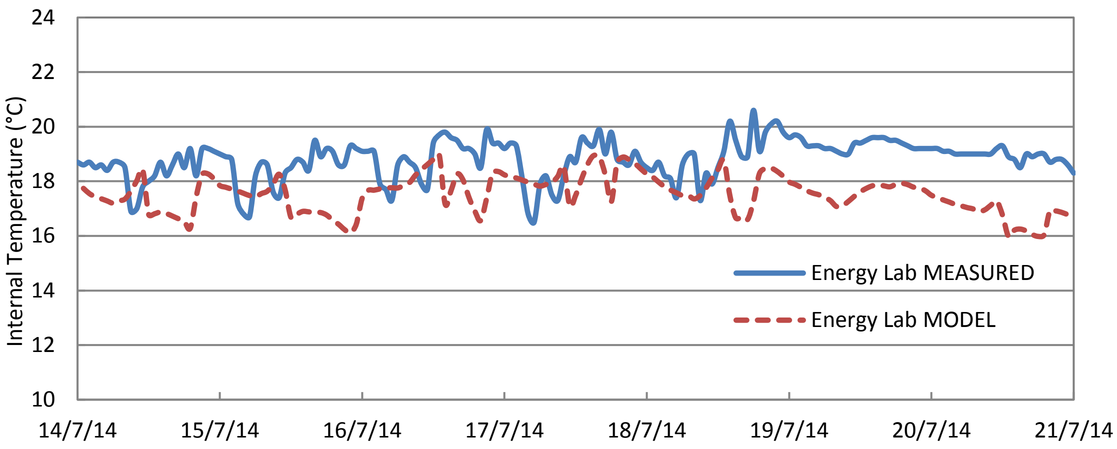


Figure 4-13 SBRC energy lab temperature profile comparison – winter.

The indication of degree of correlation, $R^2$, shows a poor result, with a very low correlation between the model and the measured data for this room across both periods. The scatter graph of the energy lab for the summer period is shown in Figure 4-15.

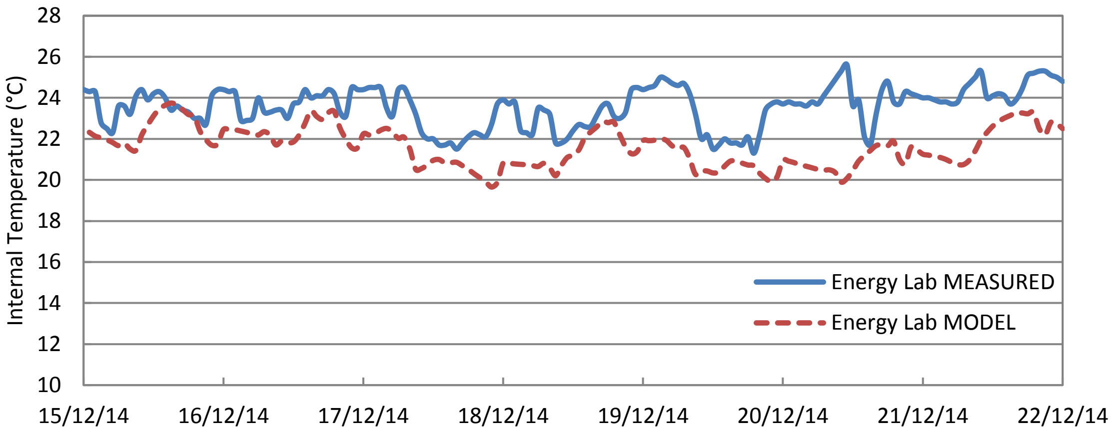


Figure 4-14 SBRC energy lab temperature profile comparison – summer.

The measured data for this room during both winter and summer periods appears to be very erratic when compared to data from the other rooms considered here. One possible cause of this may be due to the temperature sensor for the zone being located next to the entrance door. An air exchange with the adjacent space, as well as possible air flow across the temperature sensor caused by motion nearby each time the door is used may be the cause of the erratic temperature behaviours seen here. The weekend period in Figure 4-13 (from the 19/7/14) shows a moderately good correlation, albeit with some offset error. The weekend period is one where very little activity takes place in this room and thus the door is not used. This observation supports the theory that erratic readings are caused by human movement between zones. This is one aspect that cannot be considered by the model for two reasons:

i. The prediction of human behaviour is naturally very difficult to model effectively due to its random nature. Long term surveys of every entry/exit into and out of the zone may provide some insight that would enable basic modelling of characteristic behaviour but this would be beyond the scope of the modelling performed here;

ii. The temperature data output from the model is the average space temperature recorded during the specified time interval. This makes it impossible to detect the specific temperature recorded next to the doorway as recorded by the sensor installed in reality.

A better outcome would be to change the way temperature is recorded in reality for this zone. An average zone temperature would provide a better, more appropriate comparison with the data output from the model, rather than the temperature at a single point in the room, being susceptible to local effects.

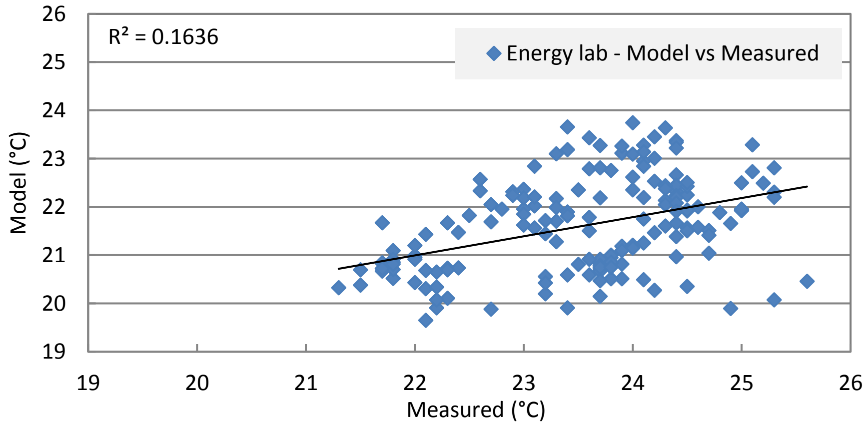


Figure 4-15 $R^2$ for energy lab room temperature comparison – summer.

Despite the less than ideal way in which temperature is measured for the zone, this is unlikely to adversely affect the outcome of the modelling performed here. A visual comparison of the temperature profiles shows similar general behaviour and an acceptable NMBE for the periods examined.

The next room at the SBRC chosen for validation is the office adjacent to the water laboratory on the ground floor. This room has east and south facing external walls and is regularly occupied by two to three people. The temperature profile comparison is shown in Figure 4-16 for winter and Figure 4-18 for summer.

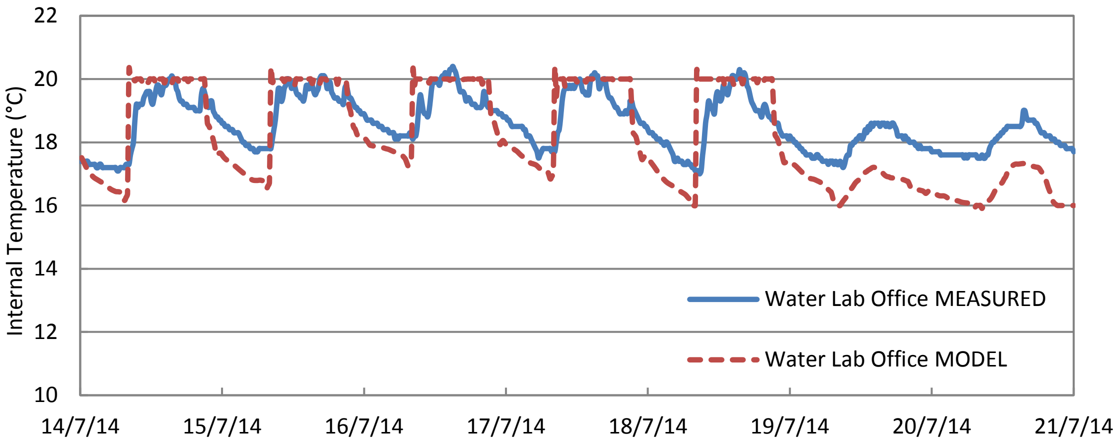


Figure 4-16 SBRC water lab office temperature profile comparison – winter.

When compared to that of the energy lab, the temperature profiles for this zone are much more predictable and thus the model does a better job of determining its thermal behaviour. The NMBE is calculated as 2.2% in winter and 4.1% in summer. The model appears to underestimate temperatures in this zone. This is most evident over the weekend, a time when no mechanical HVAC occurs, where a temperature difference of approximate 1.5°C can be observed. The zone appears to lose heat faster overnight than the real building once artificial heating has switched off.

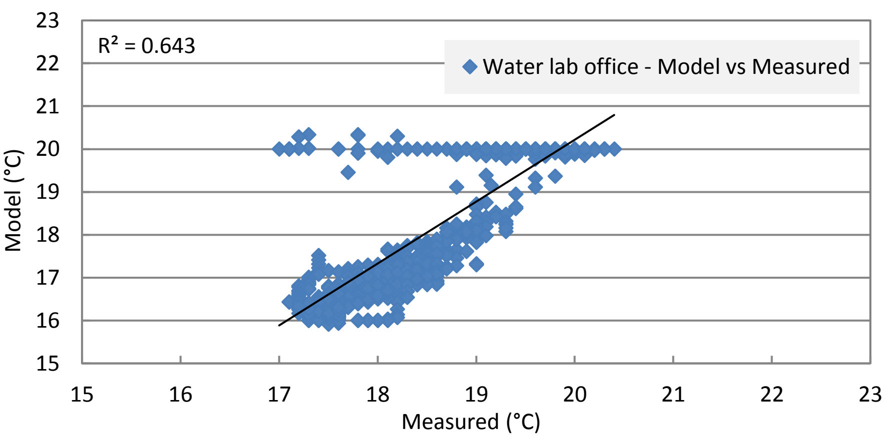


Figure 4-17 $R^2$ for water lab office room temperature comparison – winter.

The coefficient of determination of 64.3% is shown for the winter case in Figure 4-17. As was discussed previously with regards to Figure 4-5, the horizontal streak of off-trend data is due to the way the model idealises the HVAC response by maintaining the zone at a constant setpoint. This is not the behaviour experienced in reality.

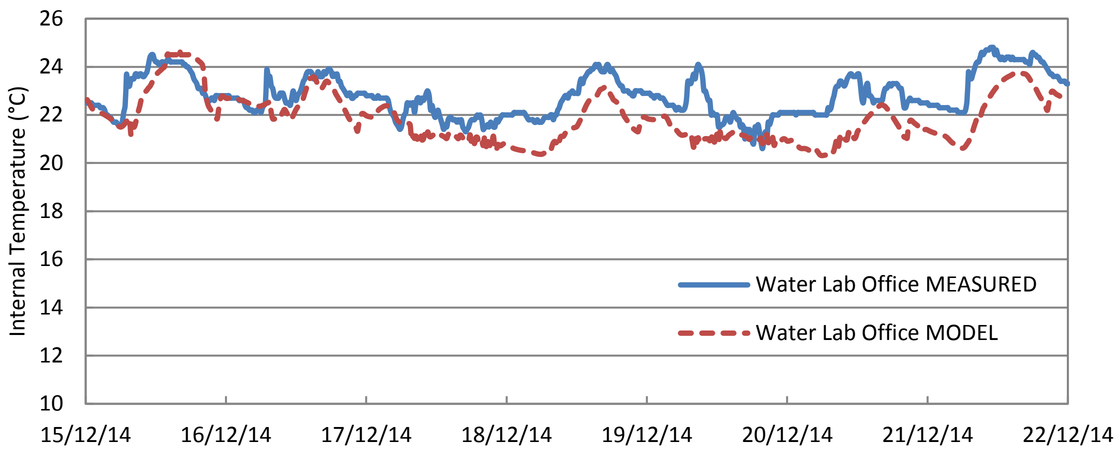


Figure 4-18 SBRC water lab office temperature profile comparison – summer.

The zone behaviour in Figure 4-18 demonstrates that the building is in natural ventilation mode in both the model and reality for the summer period. This is evident through the fact that there are few rapid decreases in temperature that are consistent with artificial cooling. The natural ventilation system is able to meet the cooling loads for that particular week. Whilst the model does not follow the real data exactly, it is considered a good result due to the fact that natural ventilation is rather difficult to model with high accuracy. A 4.1% NMBE and an $R^2$ value of 55.8% establishes a satisfactory level of representation of the real building zone.

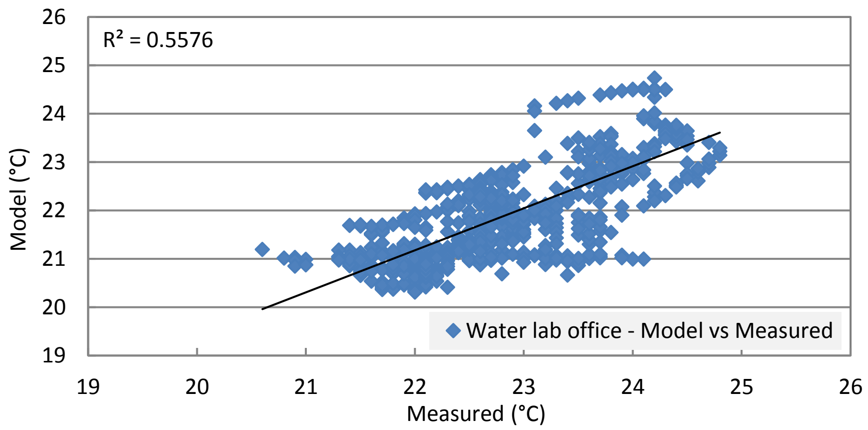


Figure 4-19 $R^2$ for water lab office room temperature comparison – summer.

The temperature profile comparison of the eastern office for the winter period is shown in Figure 4-20. This zone is at the eastern side of the building on the first floor. It is an open plan office space which is serviced by two Variable Air Volume (VAV) boxes, as well as a hydronic slab system. It is observed that the behaviour of the real building does not follow that of the model, particularly during overnight periods. A NMBE of 7.7% is calculated and $R^2$ is found to be 32.9%, as shown in Figure 4-21.

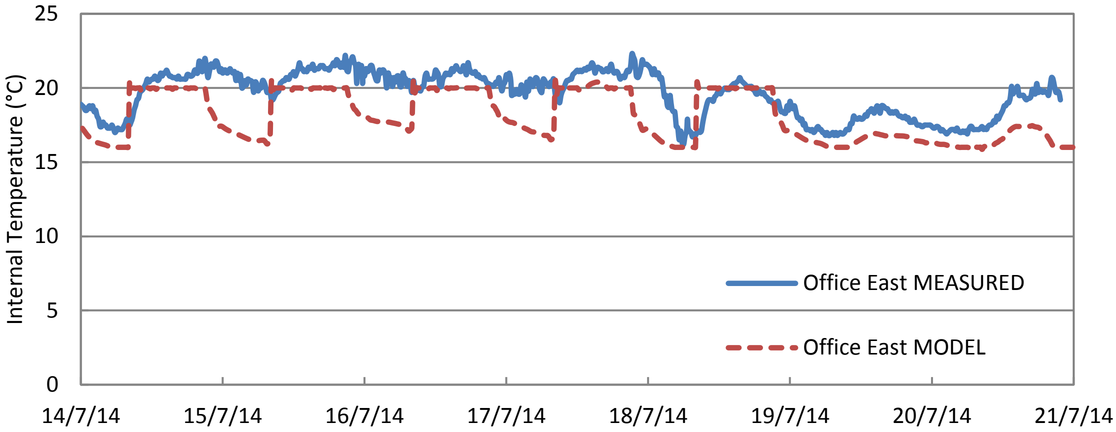


Figure 4-20 SBRC eastern office temperature profile comparison – winter.

As with previous scatter graphs, the horizontal streak of data shown at the top of Figure 4-21 is due to the way the model idealised HVAC performance and maintained temperature at a constant level. With these data points excluded, $R^2$ improves to 39.2%.

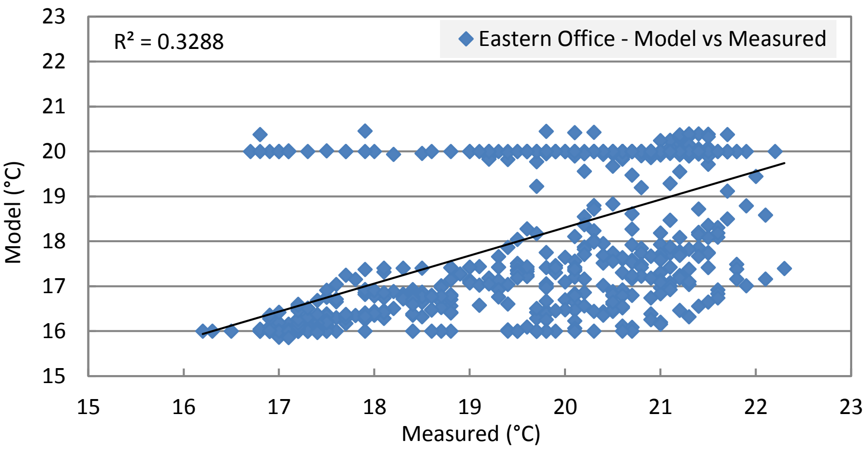


Figure 4-21 $R^2$ for eastern office room temperature comparison – winter.

One possible cause of the disparity between temperature profiles in this zone is the existence of the hydronic slab system. This system is scheduled to operate during the summer and winter months, between the hours of 4:00AM and 6:00AM. During winter, hot water is pumped through the slab, creating a slow release heat source designed to reduce heating loads during the day. Cold water is used during summer, creating a slow release heat sink.

The hydronic system installed at the SBRC was not included in this model due to the complexities of the HVAC system and the fact that the system in reality has not been properly commissioned at this stage (though it does still operate). This would make it difficult to model the system accurately when operating parameters (flow rates, fluid temperatures, etc.) have not been properly defined. The omission of this system from the model may explain why temperatures drop overnight by 3-4°C, while in the real building temperatures remain much more stable throughout the working week.

The temperature comparison for the eastern office in summer is shown in Figure 4-22. A NMBE of 3.95% is calculated. Whilst this appears to be a good result, the $R^2$ for this comparison is only 1%. There is almost zero correlation between the model and the measured temperature profiles of the week.

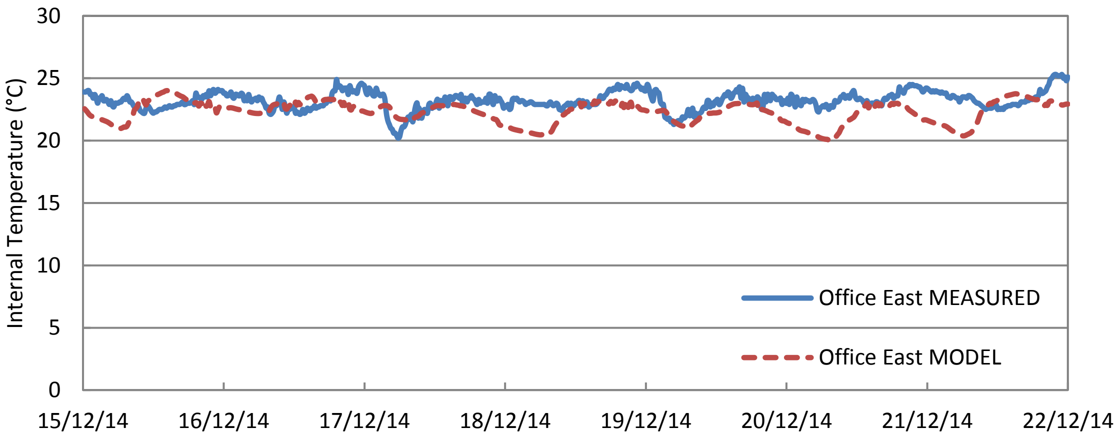


Figure 4-22 SBRC eastern office temperature profile comparison – summer.

A possible reason for this could be that the building was in natural ventilation mode for most of the week. Modelling of large, naturally ventilated spaces using this modelling technique is unpredictable given various local weather effects that are not considered by the weather file used in the simulations. Temperature profiles will not be a perfect match and thus the $R^2$ value may not be the best indicator of model success for this case. A better result might have been achieved if the large open plan zone had been modelled as several discrete thermal zones. The most important thing to consider is that the model temperature profile remained within the comfort band of 20°C to 25°C during occupied periods, which is indeed the case as shown in the figure.

Having compared the modelled temperature profiles for key building zones to the measured profiles for a summer and winter representative week, it can be concluded that the thermal performance of the building model is representative of the real building.

Whilst the model cannot fully represent in detail the temperature response of a zone in natural ventilation mode, the overall behaviour is considered to be accurate given that the zones do stay within the natural ventilation comfort band. The hydronic slab system has been ignored in this model due to it not being properly commissioned, as well as the complexity it would add to the model. Given that such little definite data is available, it would be very difficult to be able to quantify the energy implications of this system, both how much energy use can be attributed to the hydronic system, as well as how much of a net benefit it would have to HVAC energy consumption.

The validation of the energy aspects of the SBRC building model was hampered to an extent by data availability. Data was available for the lighting, and IT systems up to August 2014, and HVAC data for the entirety of 2014, however general plug loads and building services loads are unavailable as these are metered separately and technical difficulties prevented these meters from recording data. Additionally, 2014 was the SBRC buildings first official year of occupation and thus commissioning processes to building systems occurred during the early months of 2014, notably the HVAC system. Nonetheless, enough data was available to provide some degree of confidence in the model given that the most dominant building loads are represented by a sufficient amount of data.

The energy profile comparison of the modelled lighting system with the real building using daily lighting energy consumption is shown in Figure 4-23.

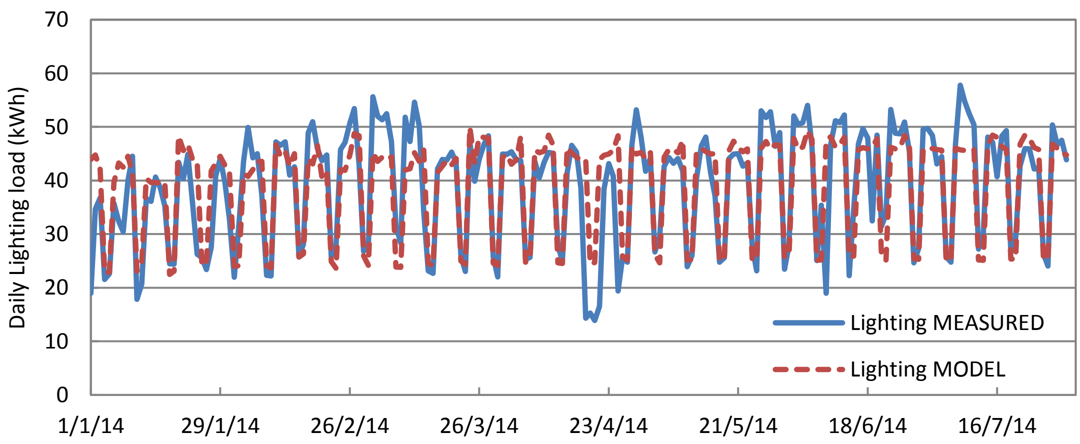


Figure 4-23 SBRC lighting electrical use comparison.

As described previously, the NMBE and the coefficient of variation of the root mean squared error (CVRMSE) are used to describe the accuracy of the energy models - in line with [73]. The NMBE and CVRMSE for the lighting model are -1.3% and 16.4%, respectively. This means that the model has overestimated the lighting loads by 1.0%. The acceptable CVRMSE limit is set at 15% which suggests this model doesn't quite fit the data available. As with the TTT building model, it should be noted that the lighting systems in these net-zero energy buildings are influenced by human behaviour and external weather conditions, with occupancy and daylight sensors controlling their operation. It is observed that on seven to ten occasions, the model underestimated the lighting energy use for the week. This may have been due to higher than normal occupancy or lower than normal natural light levels, perhaps caused by a run of days with inclement weather.

Figure 4-24 shows the IT electrical load profile comparison for the SBRC building. A NMBE was calculated as -0.3%, showing the model only slightly overestimated the IT loads of the building. The CVRMSE is 3.7%, well below the 15% limit. This shows that the IT model for the SBRC building is a good match. IT loads are one of the most easily predicted, given the load profile is very flat and operates constantly. Since VDI infrastructure is used at the SBRC, on-site IT loads are not highly influenced by occupancy. Analysis of SBRC IT energy data reveals that IT loads increase by approximately 300 W only during week days (the effect of occupancy) on top of a 1.5 kW base-load. The inaccuracies present in the model at the start of the validation period can be explained by the building being commissioned during the first month of 2014.

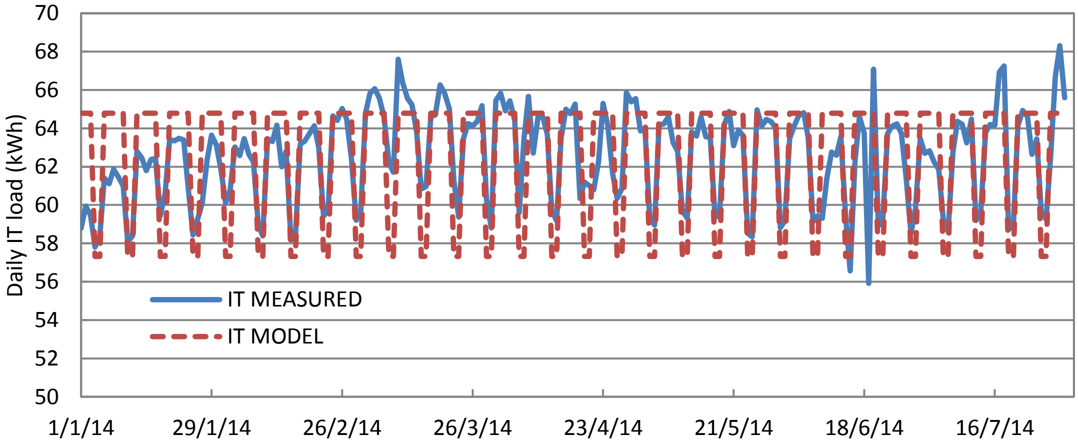


Figure 4-24 SBRC IT electrical use comparison.

The HVAC profile comparison is shown below in Figure 4-25. The NMBE is calculated as 2.7%, an acceptable value. However, the CVRMSE is 45.8%. This is far higher than the 15% limit.

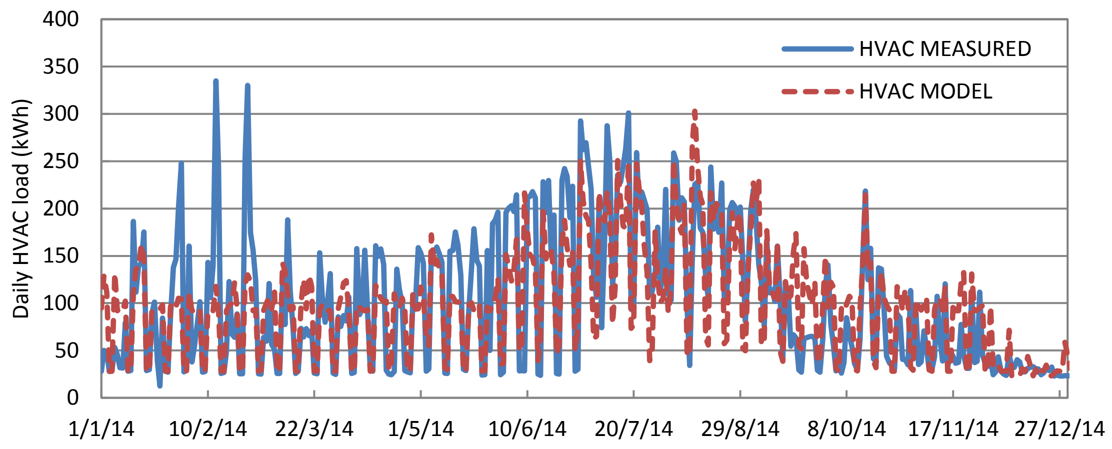


Figure 4-25 SBRC HVAC electrical use comparison.

As with the TTT building HVAC model, the model for the SBRC did not consider detailed system specifications. Rather, nominal system COP's and auxiliary loads are specified. The general operation of the HVAC system compares well on a larger timescale, with the model showing the winter period being the time of highest HVAC demand. The three peaks during the first three months of the year appear out of character and these can be explained by the building still undergoing commissioning during this time.

Having used historical weather data to compare the SBRC model simulations with real measured temperature and energy data from the same period, it must be decided whether the model is a satisfactory representation of the real SBRC building. Some aspects of the model did not meet the error quantification metrics, particularly the HVAC energy consumption. The temperature comparisons were a good fit overall with the measured data, with inaccuracies coming from the complex and unpredictable dynamics involved with natural ventilation, as well as the simplification of the model HVAC system not incorporating the hydronic slab system. With these factors considered, the thermal behaviour of the building was generally a good representation of the SBRC building for the zones considered.

The comparisons of energy aspects of the model were generally acceptable for the data that was available at the time. Whilst the HVAC model CVRMSE was three times higher than the acceptable level, the general long term behaviour of the system compared well with the measured data. There were too many unpredictable factors, as well as technical modelling difficulties associated with the HVAC model, to make it more accurate on shorter timescales.

The SBRC building model, despite the identified shortcomings, can be considered an acceptable representation of the real building for the purposes intended in this study.

### 4.4.3 Enterprise 1

Metering capabilities at the Enterprise 1 building are less extensive than at the SBRC. However, as the building has been operating for longer, more reliable data is available. For this reason, it is possible to validate the Enterprise 1 building model using a full year of energy data. Unfortunately, the energy model is only able to be validated against the HVAC system and the combined light and power loads, as the lighting system and all plug loads are metered together in the building. No separate data on IT is available.

Furthermore, temperature data for Enterprise 1 is not available. This is one difficulty encountered when studying a more conventional commercial building. Due to the SBRC and TTT being educational buildings, they have provision for research to take place within them, meaning a deeper level of information is able to be obtained. Enterprise 1, being a fully functioning commercial building, does not have this kind of information available and organising to obtain it would require a potentially lengthy planning and consultation process which could not be afforded by the timeline constraining this research. However, that given the same modelling techniques were used on the previous two buildings and that a good result was observed in those two cases, it can be inferred with some confidence that the thermal behaviour of this building is also acceptable.

The energy use comparison for the light and power systems is shown in Figure 4-26. The NMBE is 1.7%, and the CVRMSE is 5.9%. These numbers are well within the prescribed error limits. The model tends to reduce consumption from August onwards, while in reality, the opposite trend appears to occur. Apart from this discrepancy, the light and power comparison is a valid one.

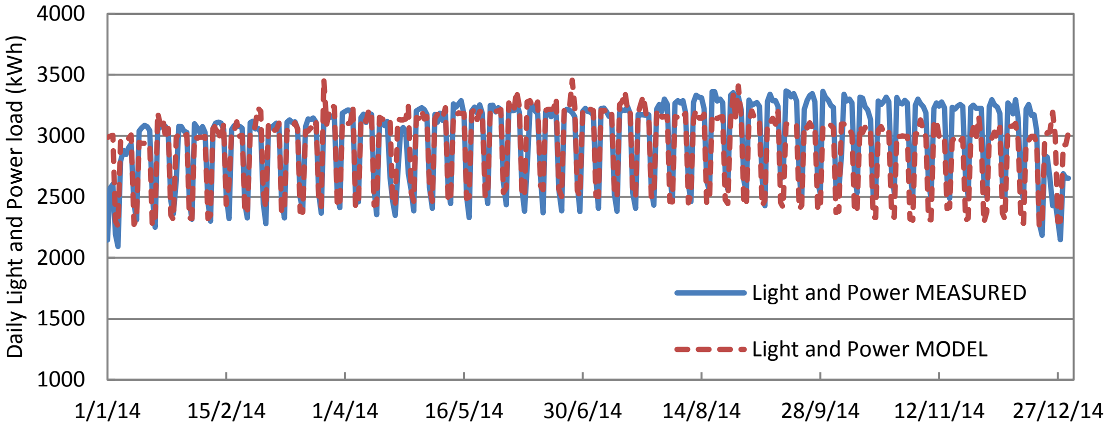


Figure 4-26 Enterprise 1 light and power electrical use comparison.

The energy use comparison for the HVAC system at Enterprise 1 is shown in Figure 4-27. A good visual comparison is observed in general. A calculated NMBE of 2.8% and CVRMSE of 21.7% confirmed that the HVAC model is the best representation out of all three buildings. Reasons for this are that the Enterprise 1 HVAC system is more conventional compared to the experimental systems installed in the SBRC and TTT buildings. The occupancy of Enterprise 1 is also higher and steadier than at TTT and SBRC which are educational buildings. This makes all electrical load profiles much more predictable.

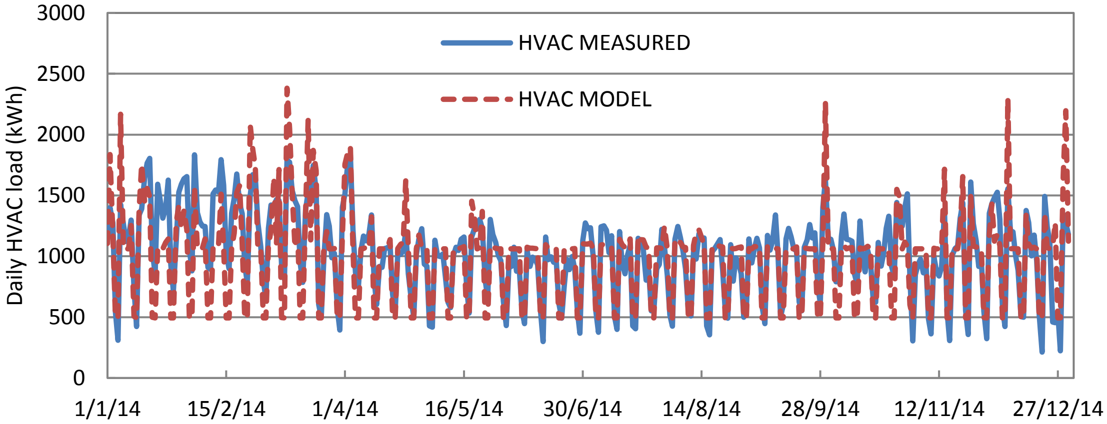


Figure 4-27 Enterprise 1 HVAC electrical use comparison.

Without a complete set of data for each separate building system, and temperature data to ensure thermal behaviour is correct, it is difficult to say that the Enterprise 1 model is a good representation of the real building. However, based on previous experience with the other two buildings which were modelled with the same techniques, we can assume with some confidence that the thermal behaviour of the Enterprise 1 model is accurate.

Not being able to separate lighting and plug loads, it is difficult to say whether the models for each individual building system are accurate on their own. It can be said however, that combined, the model does a good job of correctly representing these loads over an entire year. The same can be said for the HVAC system. Whilst the CVRMSE is higher than the prescribed limit, it is the best performing HVAC model of all three buildings.

It is with these issues in mind, that the Enterprise 1 building model can be said to be valid for the purposes of the research conducted here.

### 4.4.4 Model limitations

Any model of an existing building can only be as good as the data and assumptions used to verify it. For the three building models presented in this chapter, none of them had complete energy data able to represent each typical season of the year. The TTT building model was only able to be verified against energy data for summer and autumn. Whilst the SBRC and Enterprise 1 models had the advantage of having a full year of mechanical HVAC data, other aspects of energy use were missing or were not individually metered in the first instance. Where incomplete data is a reality, reasonable assumptions must be relied on based on typical benchmark values and technical building information. While light and power were lumped into one meter at the Enterprise 1 building, making it difficult to validate the lighting model on its own, reviewing the technical documentation on the lighting system in the real building enabled correct sizing of the system in the model. Whilst simulation results cannot be directly compared to metered building data, the assumptions used are able to be relied upon. Some assumptions are more reliable than others and depend on the accuracy of the information upon which they are based.

The validation process of efficient building models presents challenges less common for models of more conventional buildings. Highly automated systems associated with efficient buildings makes energy consumption less predictable as it is based on a higher number of variables not necessarily accounted for by the model.

## 4.5 Summary

Simulations of all three case study buildings were carried out using the real weather data. The data generated from these simulations was compared to that measured from the real buildings for the same time period and an assessment was made as to whether these building models were sufficiently representative of their real versions in order to be able to generate reliable results for the purposes of the research presented here. The assessment of thermal behaviour of the building models was performed according to two error metrics, including the normalised mean bias error (NMBE) and the coefficient of determination, $R^2$. These results are summarised in Table 4-4 where the RMSE and $R^2$ are averaged across both summer and winter periods where both are available. As the thermal data was not available for Enterprise 1, no temperature profile comparisons were therefore performed.

Table 4-4 Building model thermal behaviour error summary.

| Building | Building Zone | Average NMBE (%) | Average $R^2$ (%) |
|---|---|---|---|
| TTT | Ground floor office | -1.1 | 85.6 |
| | Seminar room | -0.5 | 78.0 |
| | Building simulation room | -7.6 | 82.6 |
| | Gallery | -10.1 | 86.4 |
| SBRC | Energy lab | 7.5 | 8.20 |
| | Water lab office | 3.1 | 60.0 |
| | Eastern office | 5.8 | 17.0 |

The assessment of the energy consumption was performed according to the NMBE, as well as the coefficient of variation of root mean square error (CVRMSE) as described in [73]. The results are summarised in Table 4-5.

Table 4-5 Building model energy use error summary.

| Building | Building system | Average NMBE (%) | Average CVRMSE (%) |
|---|---|---|---|
| **TTT** | Lighting | 12.5 | 38.4 |
| | General Power | 5.9 | 18.1 |
| | HVAC | 12.2 | 50.1 |
| **SBRC** | Lighting | -1.3 | 16.4 |
| | IT | -0.3 | 3.7 |
| | HVAC | 2.7 | 45.8 |
| **Enterprise 1** | Lighting and power | 1.7 | 5.9 |
| | HVAC | 2.8 | 21.7 |

It was only possible to work with the datasets available and as such, although validated model summaries for each building appear together in the same tables, this should not be taken to mean that consistent and perfectly corresponding periods of data were used to validate each building. Data used (where it was available) came from varying time periods. It cannot be said that every building was validated according to data occurring at the same time.

Overall, the Enterprise 1 building model appears to perform the best when viewing the numbers, however it is also the building with the least extensive metering and thus only two building systems were able to be assessed against the validation methodology.

Building size has an effect on the accuracy of the models. A larger building is less sensitive to random events that may affect energy consumption. These events are those dictated by human activity such as an occupant opening a window or turning on lights. Each occupant has differing preferences for thermal and visual comforts. In smaller buildings which have less than 50 regular occupants, such as the SBRC and TTT buildings, random events linked to occupant behaviour have more influence on energy consumption of building systems. The effect of occupants preferring to have a window open in Enterprise 1 for example, will have lesser effect on overall HVAC energy consumption than it would at the SBRC. This is one reason why the Enterprise 1 model achieved a better validation result than the other smaller buildings. Other reasons for this may be that the occupancy rate and schedules are more regular due to Enterprise 1 being a commercial building, whilst the other two buildings are for educational purposes. These buildings have variable occupancy rates and times depending on timetabling and other special events. This makes the behaviour of Enterprise 1 much easier to predict in the model, thus further reducing error.

# Chapter 5 Simulation Results and Discussion

## 5.1 Simulation Results

By performing simulations of all three buildings using the validated models in DesignBuilder, an understanding into the sensitivity of each building to changes in design and construction from the point of view of energy consumption can be gained. From this understanding, better informed decisions can be made when designing a NZEB or considering upgrades to existing buildings in order to improve energy efficiency. It is important when viewing the changes in energy consumption of one building system, that its contribution to overall building energy use is considered. After all, in most circumstances the end goal is to reduce overall building consumption, not just the consumption of one system if, consequently consumption by another system may rise. The energy use breakdown (EUB) for each building is shown below in Figure 5-1. The data used to create these EUB's is the data generated from the model outputs. Due to metering complications and inconsistencies between buildings, complete and consistent metered data could not be used to form real-world EUB's. However, as the models are representative of the real buildings, the EUB's generated are also representative of reality. Indeed, the data that was available compares well to the modelled EUB's where comparison was possible.

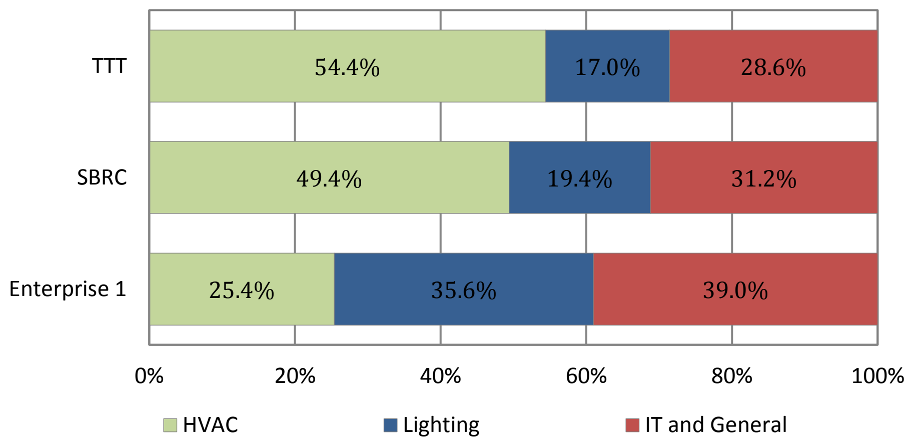


Figure 5-1 Energy Use Breakdown of three case study buildings.

From Figure 5-1 it is observed that the two NZEBs are very similar in their EUB, with lighting being the smallest component, and HVAC being roughly 50% of overall loads. On the other hand, the HVAC load at Enterprise 1 is the smallest component, making up only one quarter of overall loads. This means that different outcomes will be expected for overall energy use between the NZEB and conventional building when effects on HVAC energy use are significant.

### 5.1.1 Glazing

With the windows of a building needing to serve as both a visual connection to the outdoors, and an impermeable barrier to the outdoor elements, they form a critically important contribution to a well performing building envelope. The type of glazing used in a building can affect energy consuming building systems. Different window designs will let different amounts of sunlight into the building. This has consequences for how much artificial light is needed to sufficiently illuminate the building. Windows also allow heat to pass through them as well as visible light. Due to their transparent nature, high levels of conventional insulation are not possible in windows as they are with walls. The highest rates of heat transfer per $m^2$ through a building envelope typically take place through the windows [34]. For a building with a high window to wall ratio, this can mean significant overall heat loss occurs through the building envelope. The result of this is that HVAC loads are increased and energy consumption is driven up. Whilst having more windows may mean that lighting energy consumption may come down, it is likely that HVAC energy consumption will increase. It is this balance that will be better understood by simulation of the test cases.

Before detailed modelling results are outlined, it is important to ensure window performance terminology is correctly understood. Solar Heat Gain Coefficient (SHGC) is a measure of how well the radiant energy from sunlight is transferred through the window and thus adds heat to the space. It is defined as the fraction of incident solar radiation transferred through glass (sometimes is it specified as the glass and frame) and is expressed as a number between 0 and 1 [81]. A higher SHGC will potentially allow more heat to pass into the internal space. This may have benefits in a colder climate, and certainly has disadvantages in warmer climates.

Visible transmittance is a measure of how much daylight passes through the window and is also expressed as a number between 0 and 1. A higher number means more light is transmitted. This parameter concerns only light in the visible spectrum.

U-value (otherwise known as thermal conductance) is a measure of how well the window conducts heat. The U-value is used to specify many other types of building materials and is the inverse of the R-value, the parameter commonly used to specify the performance of insulation materials. U is specified in units of $W/m^2$-K. In other words, it is the rate of heat transfer per unit area, per unit Kelvin temperature difference. The U value may apply to both glass/air gap and frame, or glass/air gap only. Here, it applies to the glass/air gap only. The window frames used throughout all scenarios in this study are consistent and thus the specifications of the SHGC and U-value as being 'glass-only' should not adversely affect the analysis. The frame type is aluminium with thermal break.

Table 5-1 shows the glazing specifications for all simulated scenarios for all three buildings. A predictable downward trend is observed in most parameters as glazing scenarios progress toward the highest performance option (LowE triple glazed). Note however that Double LowE glazing performs better than regular triple glazing for SHGC.

Table 5-1 Glazing simulation scenarios.

| Glazing Scenario | Glass Type (Layer 1/2/3) | Glass Thickness (mm) | Air Gap (mm) | SHGC | Visible Transmittance | U-Value (W/m2-K) |
|---|---|---|---|---|---|---|
| **Single** | Generic Clear | 6 | - | 0.819 | 0.881 | 5.778 |
| **Single LowE** | Generic PYR B Clear | 6 | - | 0.72 | 0.811 | 3.779 |
| **Double** | Generic Clear | 6 | 13 | 0.703 | 0.781 | 2.665 |
| **Double LowE** | Generic LowE/PYR B Clear | 6 | 13 | 0.634 | 0.721 | 1.931 |
| **Triple** | Generic Clear | 3 | 13 | 0.684 | 0.738 | 1.757 |
| **Triple LowE** | Generic LowE Clear/Generic Clear/Generic LowE | 3 | 13 | 0.474 | 0.661 | 0.982 |

Building envelope parameters for each test case are summarised in Table 5-2. The ratios of window area to both floor and external wall area are also given. The window to floor ratio remains consistent across all three buildings with an average value of 0.229. When the high bay wing of the SBRC is excluded, these numbers change significantly. The high bay wing is a large 900 $m^2$ area which is naturally ventilated only, and is designed with very low lighting loads. As a result, it has a very low energy impact on HVAC and lighting systems. The window to floor ratio at the SBRC with the high bay wing excluded becomes 0.357, the highest of all three buildings. The Window to Wall Ratio (WWR) when the high bay wing is excluded becomes 0.436, up from 0.288 when the high bay is considered. This is still lower than the WWR of Enterprise 1, which is 0.710.

Table 5-2 Case study building envelope parameters.

| Building | Floor Area ($m^2$) | Window Area ($m^2$) | Wall Area ($m^2$) | Window to Wall Ratio | Window to Floor Ratio |
|---|---|---|---|---|---|
| **TTT** | 1021 | 218 | 813 | 0.268 | 0.214 |
| **SBRC** | 2600 | 652 | 2261 | 0.288 | 0.251 |
| **SBRC (ex HB)** | 1700 | 606 | 1390 | 0.436 | 0.357 |
| **E1** | 11874 | 2649 | 3730 | 0.710 | 0.223 |

The simulations performed were conducted over a period of an entire year. The simulation time interval is 1 hour. The results are compared to the single glazed scenario which, in this case is treated as the benchmark. Single glazing is not installed in the real case-study buildings, however as glazing technology in each real building varies, it is easier to compare each building to a common benchmark. Figure 5-2 shows the per cent change in yearly HVAC energy use for each glazing technology across all three buildings. As is expected, as glazing performance increases, HVAC loads decrease as a response to the reduced SHGC and U-value. It is noted that there is a small increase in energy use between the double glazed LowE option and the triple glazed clear option for all buildings. This indicates that a double-glazed option with low emissivity glass is a better choice than triple glazing in this case.

It is clear that the HVAC energy savings at the SBRC are higher than at the other buildings. This gap widens as glazing performance increases, with HVAC energy reduction at the SBRC occurring at a higher rate than with the other buildings.

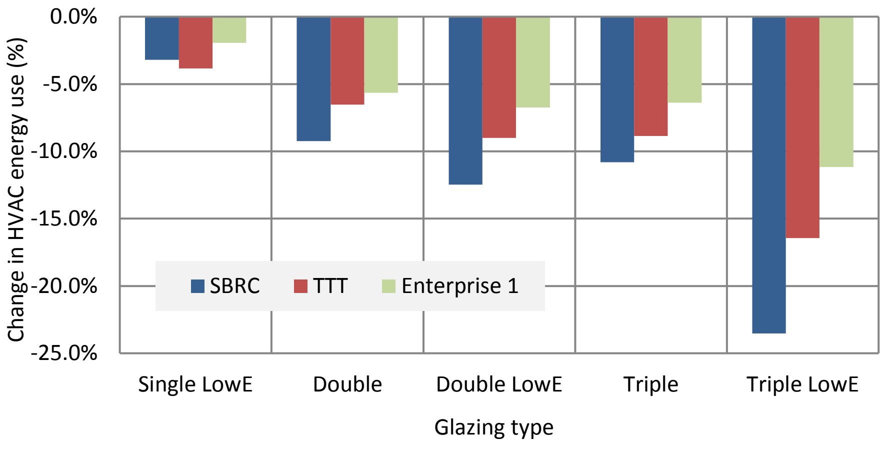


Figure 5-2 Glazing simulations: change in HVAC energy use.

The per cent change in lighting energy use for the three buildings across a full year is shown in Figure 5-3. The opposite behaviour to that seen in Figure 5-2 is observed. This is expected, since a higher performing window will typically reduce solar heat gains at the expense of also reducing visible light. Again, the difference between double glazed LowE and triple glazed clear is the opposite of the overarching trend. The magnitude of the change in lighting energy use at the SBRC building is much higher and increases at a higher rate than for the other two buildings. This is the same trend seen in Figure 5-2, but the effect is much more pronounced.

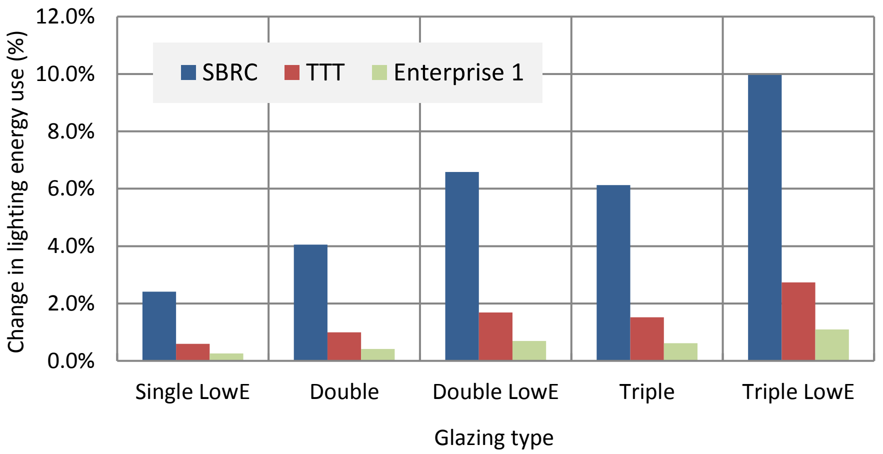


Figure 5-3 Glazing simulations: change in lighting energy use.

When the data from Figure 5-2 and Figure 5-3 is combined, the overall effect of different glazing technologies on total building energy consumption for the year is shown in Figure 5-4. Clearly the overall effect of higher performance glazing on total building energy use across a whole year is a net reduction in energy use for the three buildings studied. The building that benefits most from high performance glazing is the

SBRC, with the TTT building experiencing the second highest saving. It appears that when choosing between double glazed LowE windows and triple glazed clear, the highest performing window technology is double glazed LowE by a small margin.

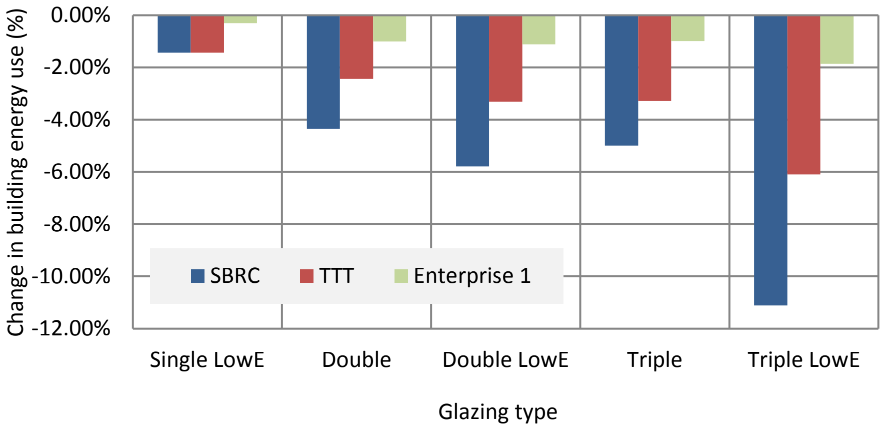


Figure 5-4 Glazing simulations: change in total building energy use.

The benefits to Enterprise 1 of high performing glazing technology are noticeable, but to a much smaller degree than the other two buildings. Whilst a maximum of 11% reduction in HVAC energy use and maximum 1.1% increase in lighting loads was predicted at Enterprise 1, a review of Figure 5-1 illustrates that the lighting energy use at Enterprise 1 represents a significantly larger portion of overall energy than that of the HVAC system. The overall net effect on the building is a 1.9% reduction in overall energy use.

To better understand why the SBRC building energy consumption may be more sensitive to changes in glazing technology, a separate set of simulations was performed where the lighting systems were identical. The lighting power density of all zones in all buildings was set at 5 $W/m^2$.

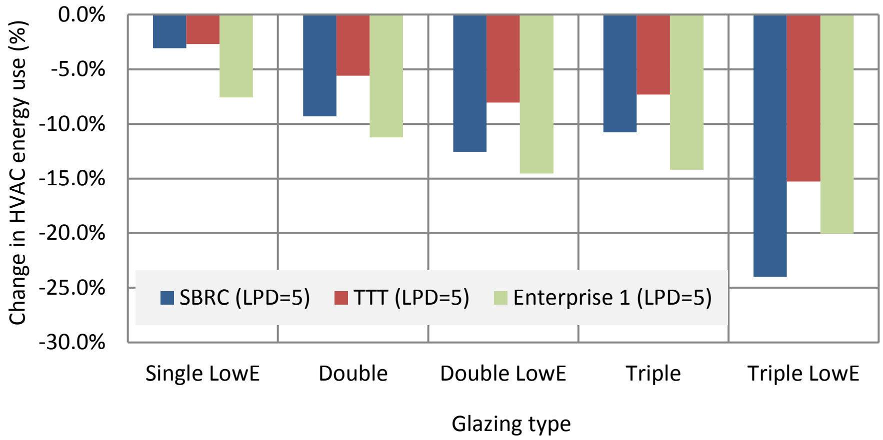


Figure 5-5 Glazing simulations: change in HVAC energy use for identical LPD.

Figure 5-5 and Figure 5-6 show the results of the simulations with identical lighting power densities. The effects on lighting energy (Figure 5-6) show the same trend as was observed previously. The increase in lighting energy consumption for the SBRC building is far higher than for the other two buildings. In fact, for an increased LPD of 5 $W/m^2$ (the actual LPD at the SBRC is 1.6 $W/m^2$), the change in energy consumption increases.

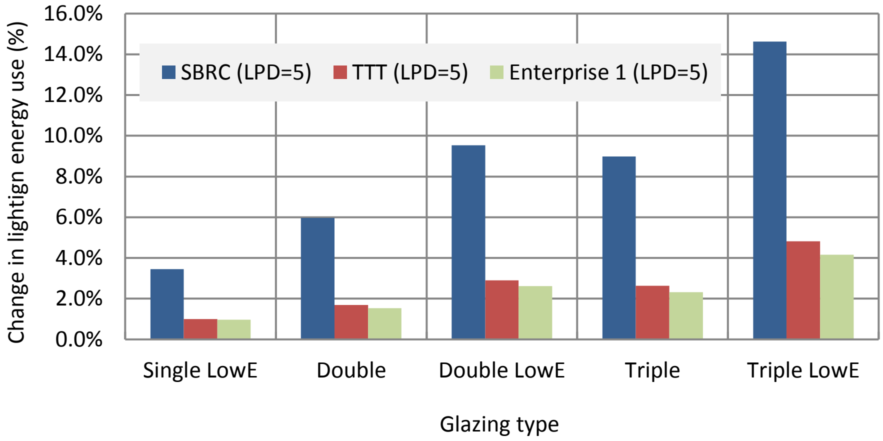


Figure 5-6 Glazing simulations: change in lighting energy use for identical LPD.

By simulating all three buildings with identical lighting power densities, it can be concluded that lighting system design is not the significant driving factor behind a building's energy sensitivity to reduced natural lighting levels caused by higher performance glazing.

To better understand what could be the driving factor in the results seen in the previous figures, data concerning the frequency of lighting system operation was analysed. For the SBRC and TTT buildings, the lighting system is controlled by occupancy and daylight sensors. If the zone is sensed as being occupied, the lighting system is able to operate. The daylight sensors determine how much light, if any, needs to be provided by the artificial lighting system.

To investigate the cause of the higher magnitude of increase in lighting energy at the SBRC, the average full load hours per week as a percentage of the total scheduled hours per week was graphed for both TTT and SBRC. Enterprise 1 does not have full daylighting control and thus the values for this building would be at 100% for all cases. The lighting systems in the models are controlled by a schedule. This is the best way of approximating occupancy in each zone. Whilst in reality, occupancy is a random phenomenon; it is in most cases, regular and predictable to a reasonable degree of accuracy. The average full load hours per week are the average number of hours for each zone where the lighting system is operating at 100% of its output potential (i.e. no dimming). The daylighting control enables the lighting system to dim to 20%. An increase in the number of hours operating at 100% would indicate lower natural light levels on average.

Figure 5-7 shows the full load lighting hours per week as a percentage of the total scheduled hours for both the SBRC and TTT building models. This term shall be known as the lighting utilisation rate. Whilst the TTT building shows a small increase in lighting utilisation of less than 1% across the glazing performance spectrum, the SBRC experiences a much larger increase of more than 4% across the glazing performance spectrum. This means that the SBRC adaptive lighting system is more sensitive to changes in daylight levels compared to the TTT adaptive lighting system.

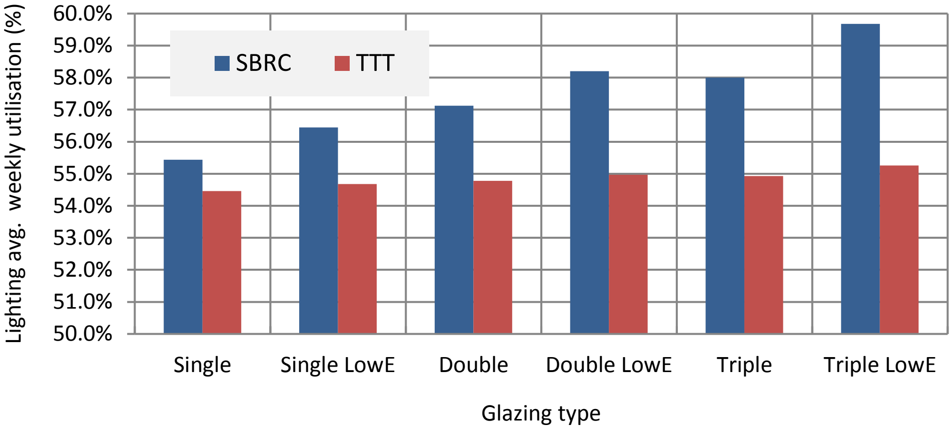


Figure 5-7 Glazing simulations: lighting system average weekly utilisation rates.

One likely reason for the SBRC building being more sensitive to variable daylight levels is building layout. Figure 5-8 shows the layout of the first floor of the TTT building. The first floor represents the majority of the building occupied floor area.

Figure 5-8 TTT building level 1 floor plan [82].

The SBRC building layout (shown in Figure 5-9) in comparison to the TTT building is much narrower in width in its two wings. The longest dimension is that running east-west. This results in an aspect ratio (the ratio of the longest dimension to shortest dimension) for each wing at the SBRC of approximately 4:1. The aspect ratio at the TTT is approximately 1.2:1 for the western portion of the building where most building activity and energy consumption takes place.

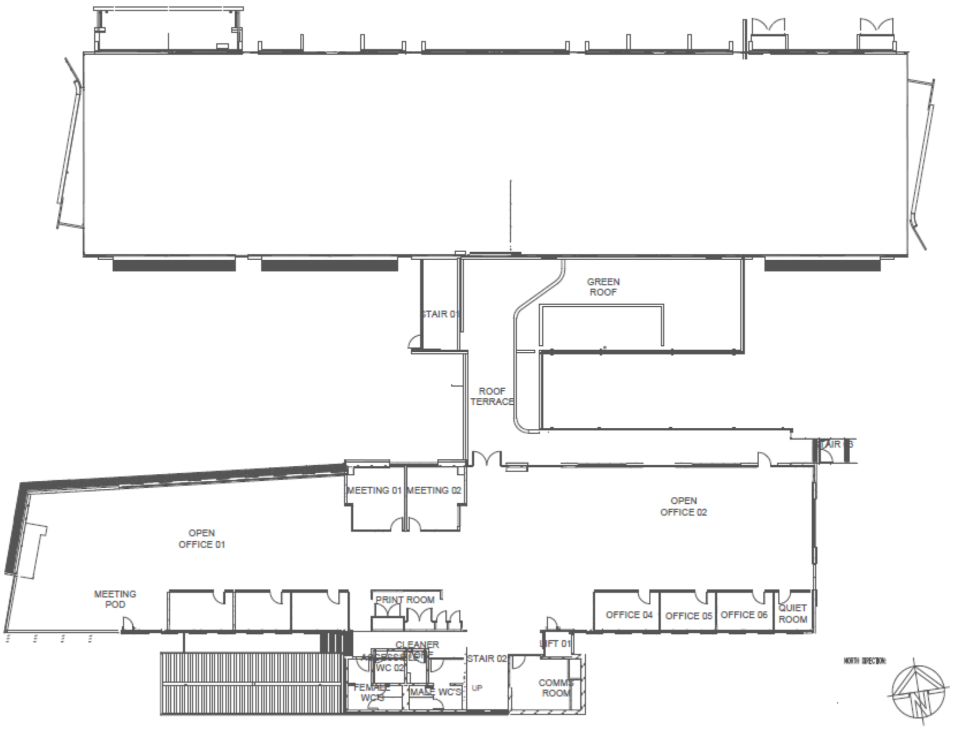


Figure 5-9 SBRC building level 1 floor plan [83].

The result of the larger aspect ratio at the SBRC building is that daylight is able to penetrate a higher proportion of the building's interior depth – reducing the overall reliance of artificial lighting in the centre of the building. Conversely for the TTT building, light is less able to reach all the way into the south facing rooms, increasing the reliance on artificial lighting. The outcome for lighting energy consumption for these two scenarios is that the TTT building must have a higher amount of installed artificial lighting and must rely on that lighting more often, while at the SBRC, a lower lighting power density is possible. Another contributing factor for the sensitivity of the SBRC building to daylight level changes is that it has the highest Window to Floor area Ratio (WFR) and Window to Wall area Ratio (WWR). This means that lighting levels inside are reduced by the greatest amount overall per square meter of floor area for all three buildings. The response to reduced daylight levels overall is an increase in light output, illustrated by the increase in average lighting utilisation shown in Figure 5-7.

The SBRC building becomes susceptible to being unable to fulfil lighting requirements when daylight levels drop due to the combination of a large window to floor ratio and low lighting power densities afforded by its high building aspect ratio. This phenomenon has been illustrated by the glazing simulations performed here where daylight transmission is reduced in higher thermally performing windows.

### 5.1.2 Lighting control

The lighting system in most buildings is a significant contributor to overall energy consumption throughout the year. For the net zero buildings studied here, the lighting systems represent an average 18% contribution to overall yearly consumption. This is contrasted with the non-net zero building, Enterprise 1, where lighting represents 36% of the overall energy consumption as seen in Figure 5-1. There are a few factors contributing to the difference in energy intensity of lighting systems between the two types of building. The first factor is the type of light fitting used. A modern, conventional commercial building will typically use T5 or T8 fluorescent tube fittings [84] while the net zero buildings use LED luminaires to a large extent. LED technology is much less energy intensive over fluorescent fittings. The result of using more efficient fittings in the building is that the lighting power density of the building is reduced. Table 5-3 shows the different lighting power densities for the three buildings. Enterprise 1 is the highest at 9.4 W of installed lighting power per square meter. The TTT building is much lower at 4.75 W/m$^2$, while the SBRC is the lowest at 1.6 W/m$^2$.

Table 5-3 Building model lighting specifications.

| | TTT | SBRC | Enterprise 1 |
|---|---|---|---|
| **Average lighting level (lux)** | 193 | 213 | 320 |
| **Average lighting power density (W/m$^2$)** | 4.75 | 1.60 | 9.40 |
| **Average LPD/100 lux (W/m$^2$-100lx)** | 2.46 | 0.75 | 2.94 |
| **Minimum output fraction (%)** | 20 | 20 | 20 |

The average lighting power density /100lux of luminous output (W/m2-100lx) is an indicator of the efficiency of the overall lighting system of the building. An efficiently lit space will achieve its designated average lighting level at a lower lighting power density.

The minimum output fraction is an indicator of how low the lighting system is able to be dimmed. It is a percentage of the maximum output.

The type of light fitting is not the only contributor to reduced lighting power density. Notice also in Table 5-3, the average lighting level in the building varies too. The lighting system at Enterprise 1 is specified at 320 lx according to Australian standard AS 1680 [85]. A 320 lux is recommended for "routine office work". The two net zero buildings have much lower average lighting levels. This is because whatever deficit there may be in overall lighting levels, localised, low power light sources are utilised on work surfaces to ensure lighting levels are appropriate. This enables much lower lighting power densities. Additionally, the increased reliance on daylighting in the net zero buildings contribute to the lower lighting power densities in those buildings.

Simulating building scenarios where different output light fittings are used could be performed. However, the result is quite predictable without having to perform whole-building energy simulations. A reduction in power consumption of each fitting is relatively constant, and thus it would be possible to calculate with reasonable accuracy, any overall consumption differences if the basic lighting specifications of each building are known. What is more interesting, and more appropriate to simulate, is lighting output control based on available daylight levels. This is a much more complex system and depends on many variables such as building design and construction, as well as weather conditions.

Each building model was simulated with and without a daylight-controlled lighting system. The results were compared below; Figure 5-10 shows the lighting energy use intensity across an entire year for each building. Lighting energy use intensity ($kWh/m_{floor}^2$) is the metric used here to enable practical comparison on one graph due to the significant differences in overall energy use across the three buildings. The results show that the energy use attributed to lighting can be reduced by between 49 and 65%. Enterprise 1 would benefit greatly from daylighting control because of its high window to wall ratio. An older style of conventional building may not respond as well to this type of lighting control since daylight may not as readily reach into the centre of the building. Enterprise 1 office space is centred on a heavily lit atrium area with large skylights that would convey a large amount of daylight into the space.

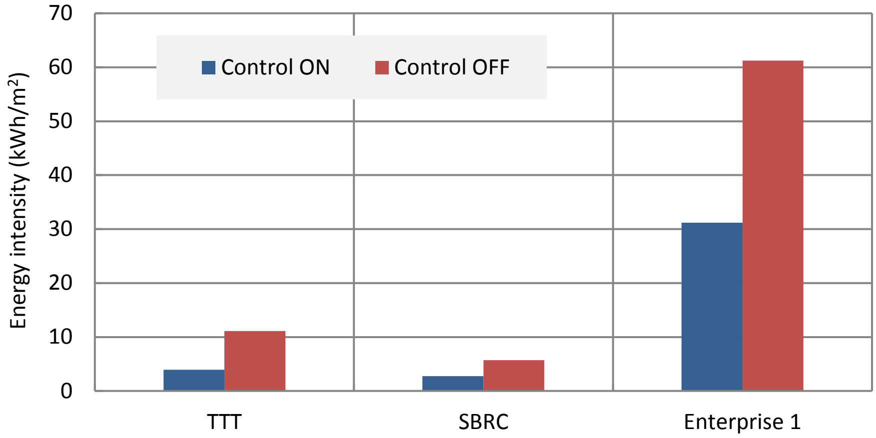


Figure 5-10 Lighting control simulations: yearly lighting energy use intensity.

The effect on the HVAC system from daylight controlled lighting is show in Figure 5-11. Overall, there is a saving as a result of reduced lighting use resulting in less waste heat output. The Enterprise 1 building model predicts the biggest saving of the buildings with a 10% reducing in HVAC energy use intensity. Much of this saving can be attributed to the waste heat from fluorescent lights being reduced. This saving is less significant in the other two buildings because the more efficient lighting technology used there does not emit as much waste heat. Savings in HVAC energy use intensity for the net zero buildings are between 2% and 5 %.

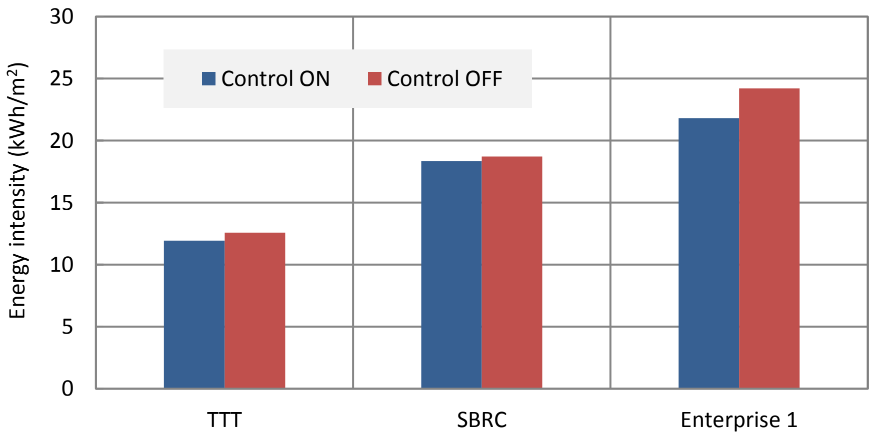


Figure 5-11 Lighting control simulations: yearly HVAC energy use intensity.

Considering the effects on lighting and HVAC energy consumption, the net effect on overall building energy consumption was compared between the three buildings. Figure 5-12 shows the yearly building energy use intensity for each building. The results show that the Enterprise 1 building would have the greatest net benefit from daylight controls with a very significant 25% reduction in overall building energy use. The TTT simulation suggests that the building experiences a 21% overall energy saving as a result of daylight controls. The smallest impact is seen at the SBRC where only 8% of energy savings can be attributed to daylight controls.

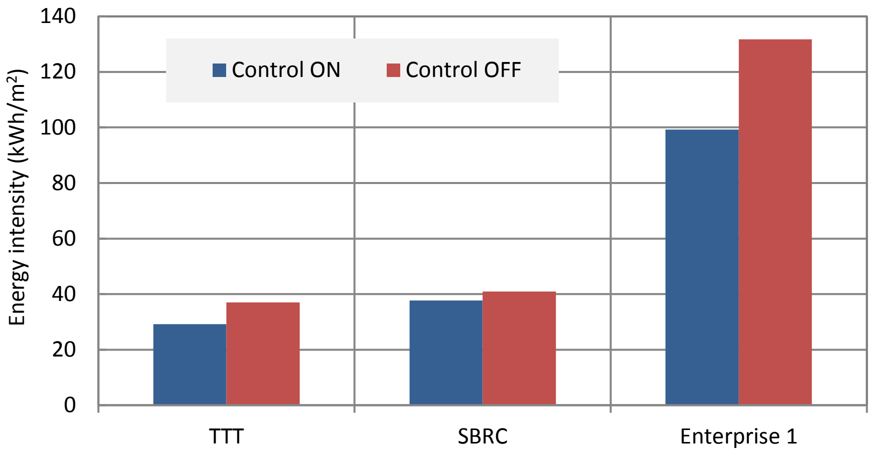


Figure 5-12 Lighting control simulations: yearly building energy use intensity.

The reason daylight controls at the SBRC contribute to such a small overall saving is that the installed lighting power density is so low because of the building being optimised to take advantage of maximum daylighting levels. It is a different story at the TTT where a higher provision of artificial lighting is installed. Whilst it is a NZEB, the installed lighting power density is three times higher than at the SBRC because of the lower aspect ratio and its implications for daylighting as described previously in Section 5.1.1.

### 5.1.3 Window shading

There are many potential techniques and design principles that may be applied to the shading of a building. Primarily the purpose of shading, no matter how it is applied, is to reduce the cooling loads in a building and to optimise the quality of daylight entering the interior of the building by controlling glare levels. For these reasons, it comes as no surprise that incorporation of shading elements is of critical importance to net zero energy building design. Shading can be implemented in a number of ways. Some of these are integral to the building's design and construction, such as a roof overhang, which must be designed to maximise the transmission of low winter sun, while minimising the transmission of high winter sun. Other techniques are incorporated into the building envelope such as vertical or horizontal louvres placed in front of a window's external face. These building-integrated shading approaches require a high degree of knowledge of building design principles, as well as information about the building site, such as nearby structures, landmarks, vegetation and building orientation. A simpler approach to shading is simply implementing shading of windows using blinds or curtains. These are typically controlled by occupants to suit their personal tastes and comfort requirements. Window shading may also be effective in some cases at reducing energy consumption.

For the purposes of this study, simulation of local, building-integrated shading will be ignored due to the need for it to be designed specifically according to the building and its location. This would make it difficult to compare results between the case study building models. Horizontal slatted blinds will be investigated instead. A common type of window shading and a common control method across all buildings will be easily comparable. The blind type used in this study is a blind with high reflectivity slats which is provided as a default in the DesignBuilder library. A description of each control strategy modelled is given in Table 5-4.

Table 5-4 Shading simulation control strategies.

| Shading Control Strategy | Description |
|---|---|
| **Summer day** | Blinds closed between 7:00 and 19:00 for all summer days (from 1st Dec to 28th Feb) |
| **Summer night** | Blinds closed between 19:00 and 7:00 for all summer nights (from 1st Dec to 28th Feb) |
| **Winter day** | Blinds closed between 7:00 and 19:00 for all winter days (from 1st June to 31st Aug) |
| **Winter night** | Blinds closed between 19:00 and 7:00 for all winter nights (from 1st June to 31st Aug) |
| **Temperature 26°C** | Blinds closed when outdoor temperature is above 26°C at all times of the day |
| **Temperature 28°C** | Blinds closed when outdoor temperature is above 28°C at all times of the day |
| **Temperature 30°C** | Blinds closed when outdoor temperature is above 30°C at all times of the day |
| **Temperature 32°C** | Blinds closed when outdoor temperature is above 32°C at all times of the day |

The window shading implemented here in this study does not replace any building integrated shading elements in the original design. Some degree of shading is present in each test case in the form of roof overhangs, window louvres, or both. These are left as-designed in the building models. The window shading studied here is in addition to the originally designed and built-in shading elements of the building envelope. The results are compared to a benchmark where these local shading elements do exist, but where no window shading is used.

The change in lighting energy use because of window shading controlled according to the season is given in Figure 5-13.

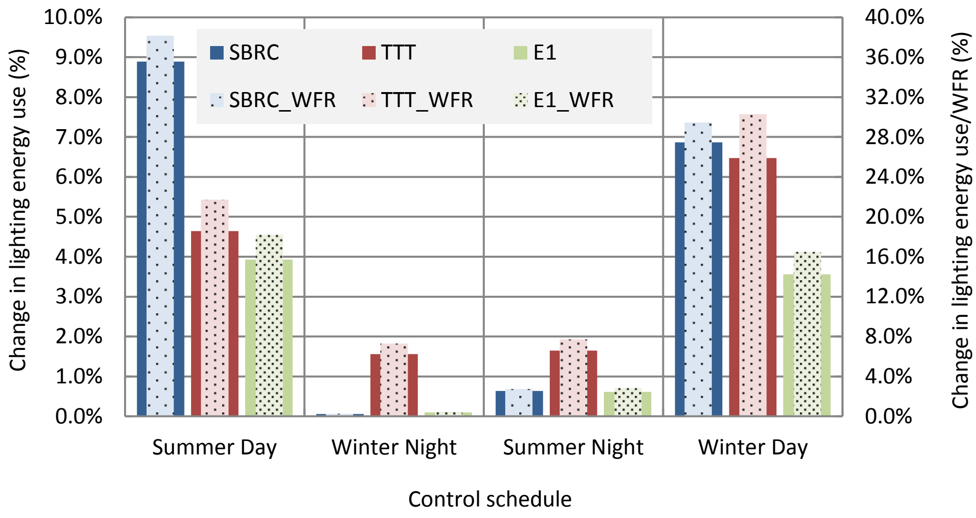


Figure 5-13 Shading simulations: lighting energy use, seasonal schedule.

Unsurprisingly, the result is an increase in lighting use when shading is implemented during the day for both summer and winter. The SBRC building model appears most sensitive in summer, while Enterprise 1 is the least sensitive. Both the TTT and SBRC experience a similar degree of change for the winter daytime case. Since all three buildings are primarily occupied only during the daytime, only small changes were seen for the summer and winter night time control cases.

The lighter colour, patterned columns on the graph represent the per cent change in lighting energy use in proportion to the window to floor area ratio. Whilst this is not necessarily a useful metric with which to specify a building or lighting design by, it is a nominal dimension which does give an indication of the comparative sensitivity of the buildings to window shading. From the graph, the comparative magnitudes of these values are largely similar to those of the absolute change in lighting energy use. This indicates that the WFR is likely to be the determining factor in the degree of change in energy consumption for the lighting system. To make sure of this, the per cent change in lighting energy use is also compared to the window area on its own. This is shown in

Figure 5-14. When compared to window area alone, the units are multiplied by a factor of 1,000 to scale the values up due to window areas being much larger than the per cent change in energy.

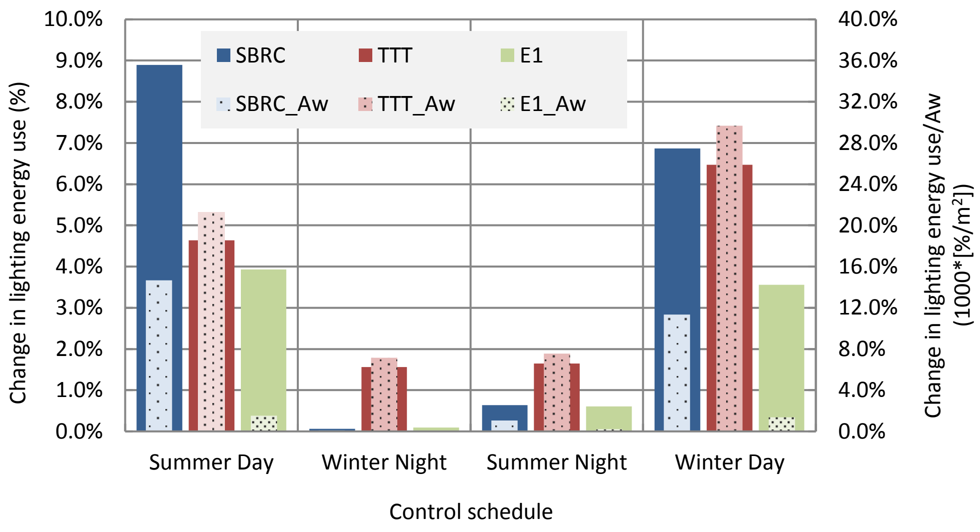


Figure 5-14 Shading simulations: change in lighting energy/$A_{window}$ - seasonal.

A different behaviour is observed when the per cent change/window area ($A_{window}$) is examined. The TTT building experiences a larger per cent change / area of window than that of the SBRC and Enterprise 1 models. This makes sense since it has the smallest total window area of the three buildings.

Comparing the change in HVAC energy use as a result of shading according to a seasonal control strategy, Figure 5-15 shows that similar behaviour was observed as in Figure 5-13 but with reversed changes, the HVAC loads decrease during the summer day due to a cut in heat gain through the windows. Little change is observed for the summer and winter night time control strategies, but interestingly HVAC energy use increases for the case where shading is implemented during winter days. This is because solar heat gain through windows helps to reduce heating loads during these periods. The TTT building benefits most from this effect since the HVAC energy use increases by 16% when solar gains are reduced through shading. At the SBRC, HVAC energy use increases by only 8%. Little change is observed for Enterprise 1.

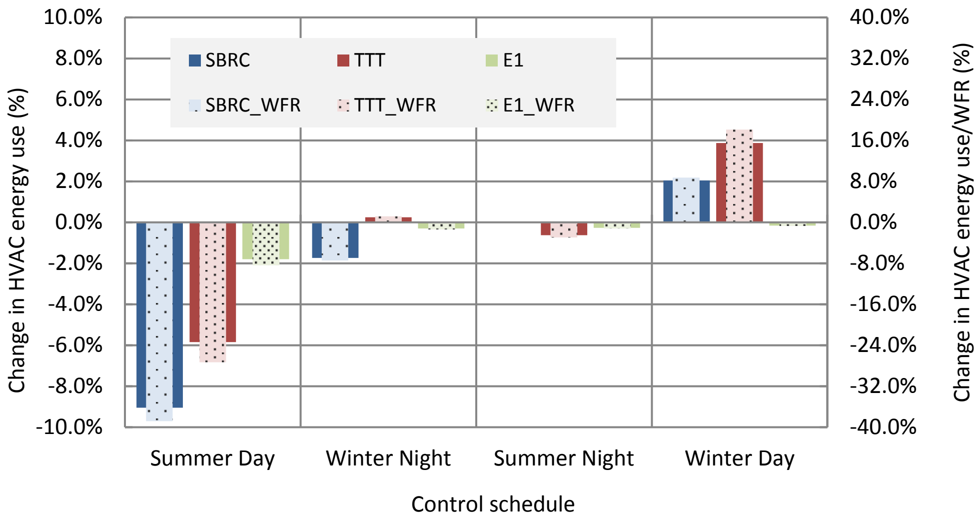


Figure 5-15 Shading simulations: HVAC energy - seasonal schedule.

Once again, comparing the change in energy use/window to floor area ratio, with the change in energy use/window area gives some indication of what the determining parameter is with regards to the buildings' sensitivity to shading levels. The change in energy use/window area is shown in Figure 5-16. The behaviour observed is similar to that in Figure 5-14, where the TTT building appears to experience the largest per cent change in HVAC energy use per $m^2$ of window area.

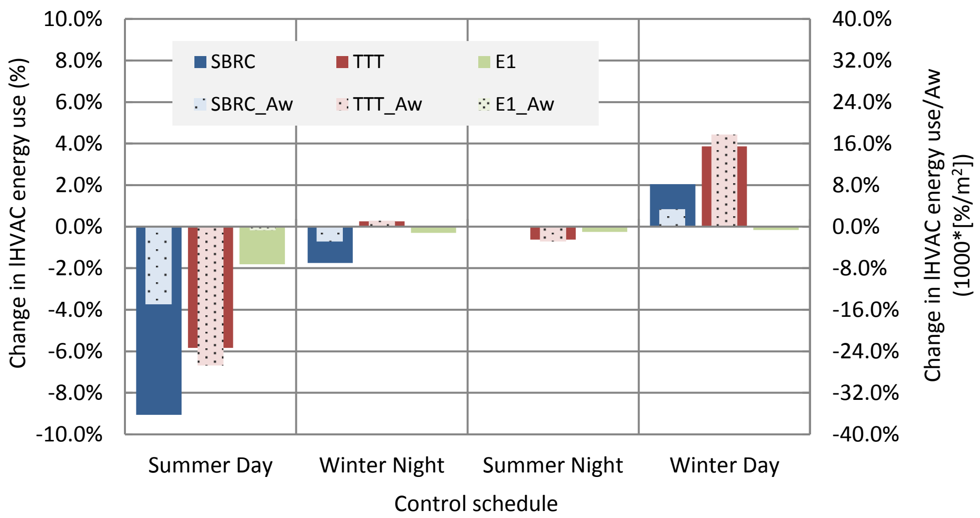


Figure 5-16 Shading simulations: change in HVAC/$A_{window}$ - seasonal schedule.

It is not until the relationship between floor area and window area is considered, that it becomes clear that this parameter is closely aligned with the relative changes in energy use for both lighting and HVAC.

The changes in lighting and HVAC energy for window shading using a temperature threshold control strategy are shown in Figure 5-17 and Figure 5-18. What is most obvious is that the biggest changes come from lower temperatures, with the largest effect being seen at the SBRC for both lighting and HVAC. The increase in lighting energy at the TTT and Enterprise 1 were of similar magnitude of around 1.5%, while the decrease in HVAC energy at the TTT compares more closely with the SBRC at around 3.6 to 4.8%.

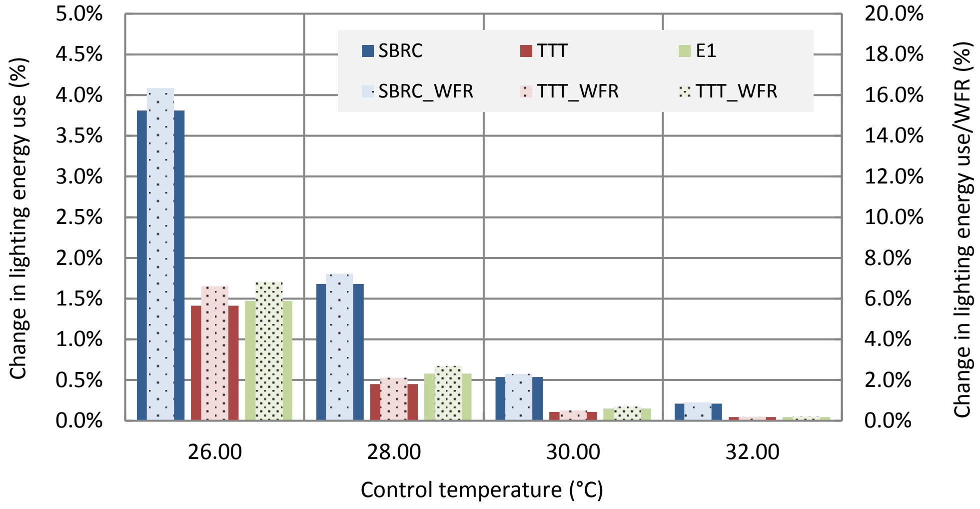


Figure 5-17 Shading simulations: lighting energy use - temperature control.

Interestingly, changes in energy consumption decrease as the threshold temperature for implementing shading increases. The minimum temperature of 26°C is chosen as being just above the cooling setpoint temperature for each of the three buildings. Temperatures below this would interfere with the natural ventilation strategies implemented in the NZEBs.

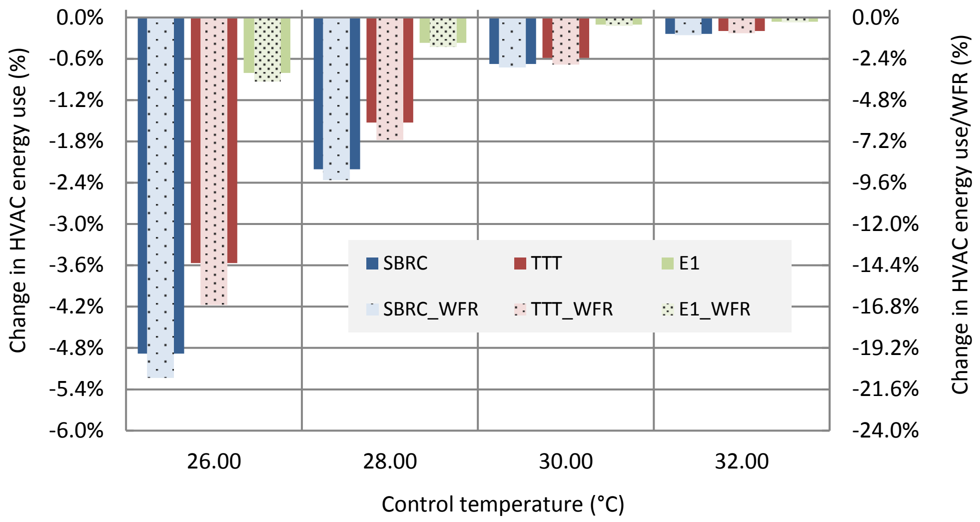


Figure 5-18 Shading simulations: HVAC energy use - temperature control.

To understand why the changes in energy consumption diminish as the threshold temperature increases, the temperature histogram of the weather file used in each model will be examined. This histogram is shown in Figure 5-19. The average temperature for the Typical Meteorological Year is 17.5°C, which the maximum is 34.3°C. The most relevant detail here is the frequency of temperatures 26°C and above.

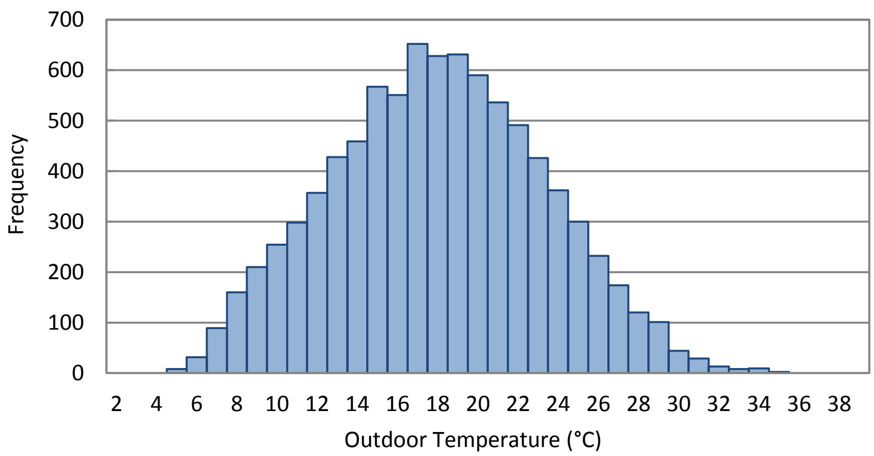


Figure 5-19 Bellambi TMY weather file temperature histogram.

Temperatures in this range occur only 8.14% of the time, with temperature occurrence decreasing steadily from 26°C.  Figure 5-20 shows the rate of occurrence of temperature 20.6°C and above for the TMY weather file used in this study. This explains why the magnitude of changes in energy consumption decrease as shading threshold temperature rises. In a more extreme climate than Wollongong, this behaviour would be expected to be different.

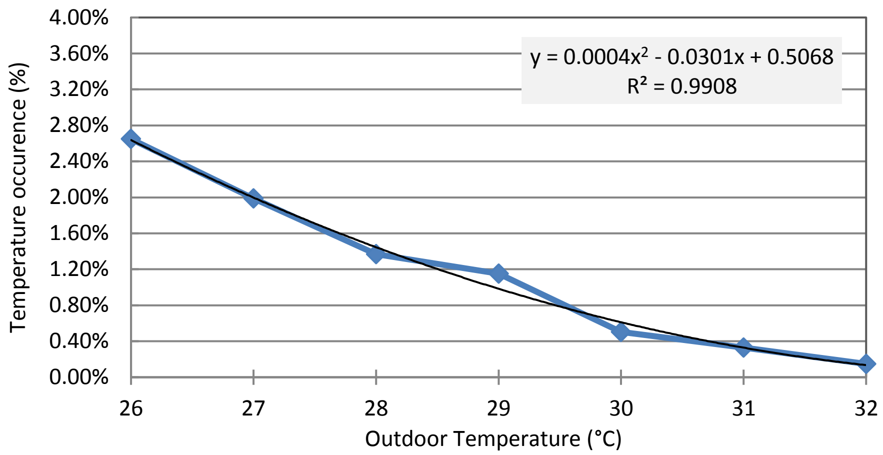


Figure 5-20 Occurrence of outside temperatures above 26°C.

The overall net effect on building energy consumption for the two different control methods are shown in Figure 5-21 and Figure 5-22.

For the seasonal shading control, the most effective strategy for the net zero buildings is to close all blinds during summer days. The models predict that this will result in a saving of 1 to 4% overall. For Enterprise 1, this will have the effect of increasing overall consumption by around 1%. This is because lighting in this building makes up a higher proportion of energy consumption than the HVAC system. Shading windows during winter nights also results in a net reduction in overall consumption for the SBRC building model due to a reduction in HVAC loads as a result of the building being better able to retain heat overnight. The opposite observation is made for the TTT building due to an increase in lighting use as a result. Negligible effects on building energy consumption are observed for all three of the buildings when shading is used during summer nights. Significant increases in overall energy use when shading is used during winter days are observed. This is caused by increases in both lighting and HVAC use in the order of 3 to 8% for the net zero buildings, while Enterprise 1 sees negligible changes in HVAC loads, but a 3.5% increase in lighting loads resulting in a 1.3% increase in overall consumption.

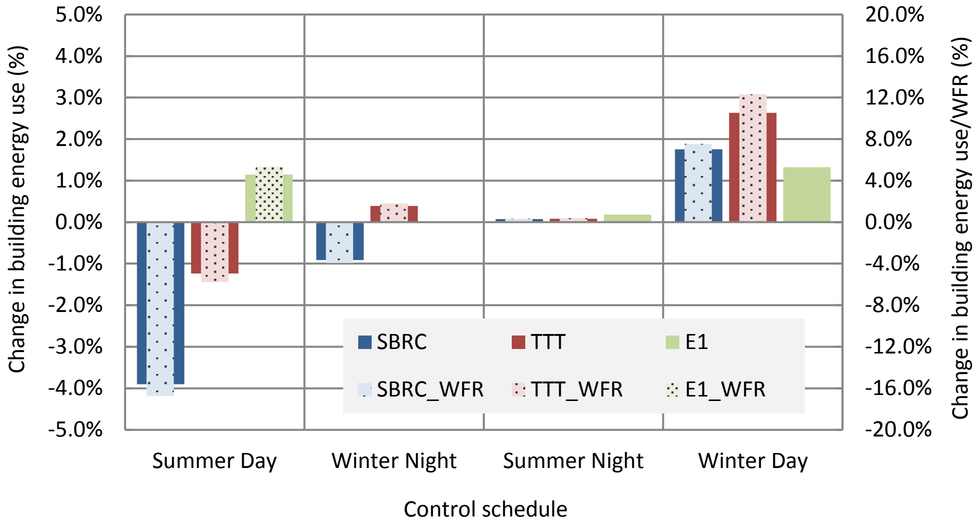


Figure 5-21 Shading simulations: building energy use - seasonal schedule.

Where shading is controlled according to the outdoor temperature threshold, the net zero buildings experience savings of between 1% and 2% for the 26°C case, while Enterprise 1 experiences a slight increase for all temperatures above 26°C.

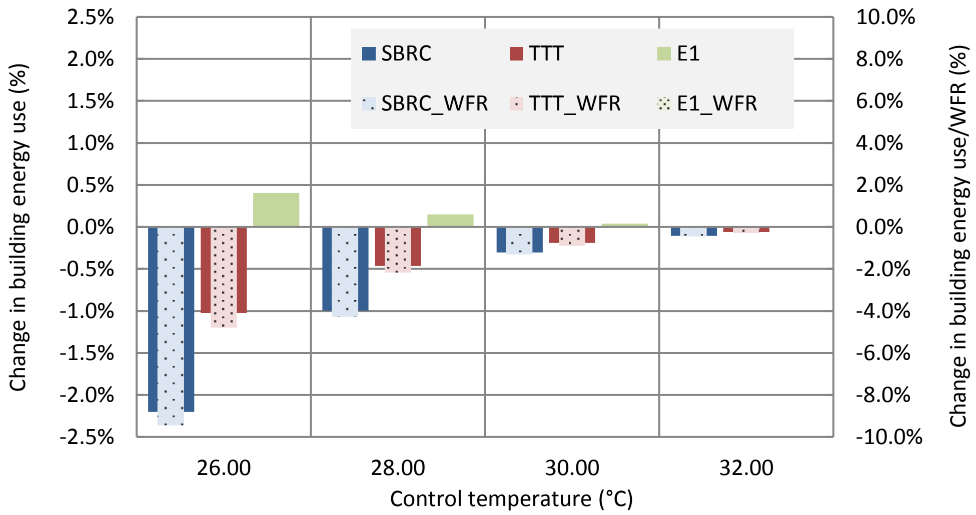


Figure 5-22 Shading simulations: building energy use - temperature control.

Overall, window shading of all three of the case study buildings resulted in only marginal net energy savings for the type of shading and control strategies investigated. The Enterprise 1 model experienced a net increase in overall consumption for all cases because of lighting loads being larger than HVAC loads and the higher sensitivity of the lighting system to window shading. The net zero buildings, with their much lower lighting loads, were able to achieve overall savings, however these were of a small magnitude: 3.9% was the maximum saving for the SBRC building and 1.2% for the TTT building. The savings found here must also be balanced with perceptions of comfort for occupants, as well as convenience. Spending the entire work day in a room effectively without windows is unlikely to be a pleasant workplace.

### 5.1.4 HVAC setpoint

Given that HVAC systems in buildings are typically a major consumer of energy, optimisation of these systems is a worthwhile endeavour to reduce overall consumption as much as possible.

The study performed here was to evaluate the impact of changing the heating and cooling setpoint temperatures on energy use. The heating setpoints were varied in one-degree increments from the benchmark while the cooling setpoint was kept constant. For example, for the Heating -3° scenario, the heating setpoint is lowered by 3°C from the benchmark, while the cooling setpoint remains set at the benchmark. Where natural ventilation was employed (in the two NZEBs), the lower limit of this range followed the heating setpoint up and down. Conversely, the cooling setpoint was then varied in 1-degree increments while the heating setpoint was held constant. A dead band/hysteresis region of 0.5°C exists between modes to ensure different modes are not toggled repeatedly on mode borders. This incorporates as 20-minute switching delay. The upper limit of the natural ventilation range followed the cooling setpoint up and down. A range of three degrees was chosen for the net zero buildings since the comfort bands in these buildings are wider than that of Enterprise 1. The range was two degrees at Enterprise 1 due to not being able to increase the heating setpoint, or decrease the cooling setpoint any further without overlapping into the other's range. The complete methodology is shown in Table 5-5.

Table 5-5 HVAC setpoint simulation methodology.

**TTT & SBRC**

| TTT & SBRC Benchmark Case | Heating 19.5 °C | NV | Cooling 24.5 °C |
|---|---|---|---|
| Heating +1 | Heating 20.5 → | NV | Cooling 24.5 |
| Heating +2 | Heating 21.5 →→ | NV | Cooling 24.5 |
| Heating+3 | Heating 22.5 →→→ | NV | Cooling 24.5 |
| Heating -1 | ← Heating 18.5 | NV | Cooling 24.5 |
| Heating -2 | ←← Heating 17.5 | NV | Cooling 24.5 |
| Heating -3 | ←←← Heating 16.5 | NV | Cooling 24.5 |
| Cooling +1 | Heating 19.5 | NV | Cooling 25.5 → |
| Cooling +2 | Heating 19.5 | NV | Cooling 26.5 →→ |
| Cooling +3 | Heating 19.5 | NV | Cooling 27.5 →→→ |
| Cooling -1 | Heating 19.5 | NV | ← Cooling 23.5 |
| Cooling -2 | Heating 19.5 | NV | ←← Cooling 22.5 |
| Cooling -3 | Heating 19.5 | NV | ←←← Cooling 21.5 |

**Enterprise 1**

| Enterprise 1 Benchmark Case | Heating 21.0 °C | Cooling 24.0 °C |
|---|---|---|
| Heating +1 | Heating 22.0 → | Cooling 24.0 |
| Heating +2 | Heating 23.0 →→ | Cooling 24.0 |
| Heating -1 | ← Heating 20.0 | Cooling 24.0 |
| Heating -2 | ←← Heating 19.0 | Cooling 24.0 |
| Cooling +1 | Heating 21.0 | Cooling 25.0 → |
| Cooling +2 | Heating 21.0 | Cooling 26.0 →→ |
| Cooling -1 | Heating 21.0 | ← Cooling 23.0 |
| Cooling -2 | Heating 21.0 | ←← Cooling 22.0 |

Several assumptions were made in the HVAC models for each building. As discussed in Section 4.3, the HVAC models are approximated using an idealised load calculation method which uses constant coefficients of performance. This eliminated the need to specify every individual HVAC component in the system, a task which requires information that is often hard to come by, and a large amount of modelling experience in order to achieve reliable results. Because of the basic assumptions made, the HVAC model is not expected to be a true representation of the real systems; however the relative changes in overall consumption are expected to be broadly reliable based on the validations performed in Section 4.4. A summary of the key performance parameters for each HVAC model is given in Table 5-6. The coefficients of performance and natural ventilation rates are approximated through trial and error throughout the validation process as these parameters are not easily measured in reality.

Table 5-6 HVAC setpoint simulation: building model HVAC details.

| | TTT | SBRC | E1 |
|---|---|---|---|
| **Auxiliary loads (W/m$^2$)** | 3.0 | 3.0 | 5.2 |
| **Heating COP** | 2.8 | 2.8 | 1.0 (natural gas) |
| **Cooling COP** | 2.8 | 2.8 | 2.8 |
| **Heating supply air Temp (°C)** | 40.0 | 40.0 | 35.0 |
| **Cooling supply air temp (°C)** | 14.0 | 12.0 | 12.0 |
| **Natural vent. rate (Air changes/hour)** | 3.5 | 3.0 | - |

Figure 5-23 shows the change in yearly HVAC energy use at each building for each degree change in HVAC setpoint from the benchmark. The SBRC building model appears most sensitive to changes in heating setpoint, with approximately 15% change occurring for every degree increase in heating setpoint. For every degree decrease in heating setpoint, the energy consumption decreases by an average 9% per degree for the SBRC model. The TTT and Enterprise 1 models experience very similar behaviour for the heating case. Almost identical changes in energy consumption are observed for these models when the heating setpoint is increased. When the heating setpoint is decreased, the Enterprise 1 model is the least sensitive, experiencing very little change in energy consumption. Conversely, the Enterprise 1 model experiences the most rapid increase in energy consumption when the cooling setpoint is decreased. The SBRC and TTT models experience significant changes in this respect also, with a maximum of 50% increase in energy consumption when the cooling setpoint is lowered by 3°C. When the cooling setpoint is raised, the corresponding reduction in energy consumption observed for the SBRC model is the smallest of the three buildings, while the reductions for the TTT and Enterprise 1 models are quite similar.

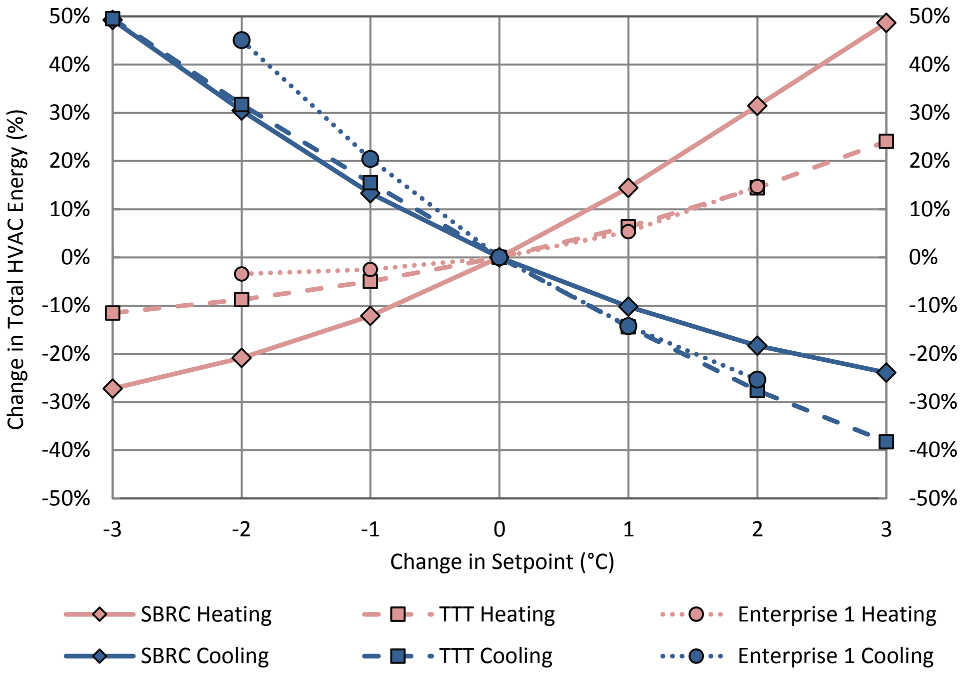


Figure 5-23 HVAC setpoint simulations: change in HVAC energy use.

To see how these changes in HVAC energy consumption translate into overall building-wide impacts, the change in total yearly building energy consumption is shown in Figure 5-24 for the three buildings.

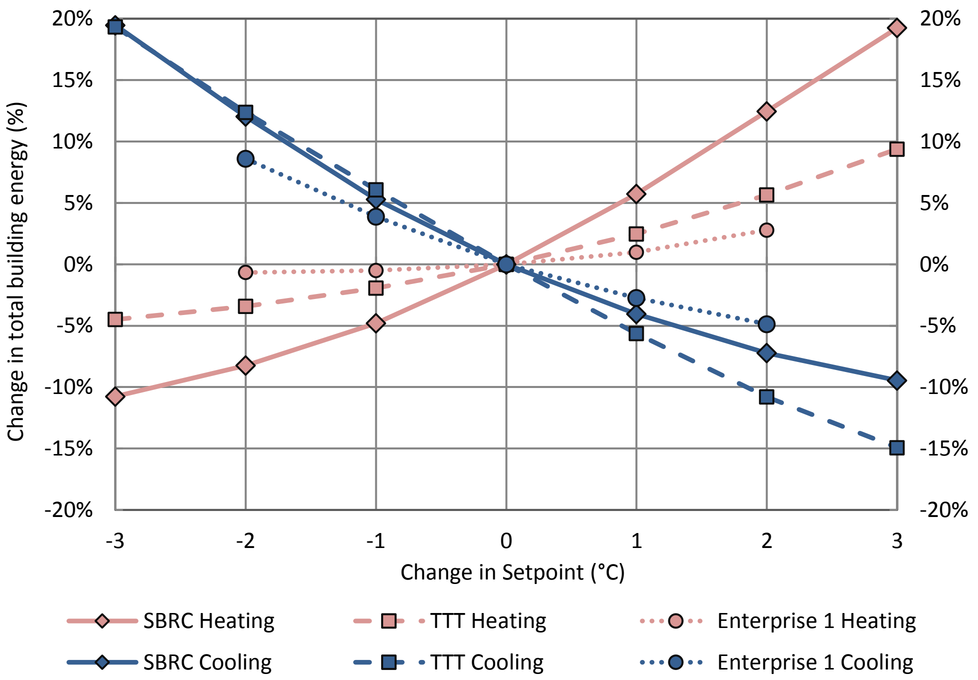


Figure 5-24 HVAC setpoint simulations: change in building energy use.

The building model most responsive to changes in heating setpoint is the SBRC. For the cooling setpoint case, the SBRC and TTT models are equally sensitive to changes when the setpoint is reduced. The TTT model is most sensitive to increases in cooling setpoint. In all cases, the Enterprise 1 model was the least sensitive to setpoint changes with negligible savings being achieved and a 2.5% energy increase being observed in the heating case. In the cooling case, the Enterprise 1 model achieved up to 5% energy saving for a 2°C increase in cooling setpoint. Where the cooling setpoint was decreased, the energy consumption of the Enterprise 1 model increased by up to 8.5%.

When considering the practical applications of the results presented here, occupant comfort must be considered. Whilst further savings of 5 to 15% may be achievable for the already efficient net zero buildings, this must be weighed against the comfort of occupants. Saving 10% in energy costs at the SBRC is unlikely to be worthwhile given that in order to achieve this, the heating setpoint must be lowered by 3°C, corresponding to a temperature of 16.5°C. Likewise, a further 15% might be saved at the TTT if the cooling setpoint was raised by 3°C. But this would mean that the new cooling setpoint was 27.5°C, beyond the acceptable comfort limits of most occupants.

The results of simulations performed here show that the Enterprise 1 model is least sensitive to changes in HVAC setpoint from an energy consumption standpoint, despite having the narrowest comfort band compared to the two NZEBs. Energy consumption at both the SBRC and TTT is seen to increase significantly when the cooling setpoint is lowered and when the heating setpoint is raised. Interestingly, the decrease in energy consumption is almost equally as significant despite the wider comfort band employed in these buildings. The reason for this likely has to do with the building EUB seen in Figure 5-1. The HVAC component of energy consumption makes up 54% and 49% of overall building consumption at the TTT and SBRC, respectively. HVAC loads at the Enterprise 1 building make up only 25% of overall building loads. This means changes in HVAC energy consumption at the net zero buildings have a greater impact on overall building consumption.

## 5.2 Summary

This chapter has presented the results of building simulation of two net zero energy buildings and one modern commercial building. Results indicated that the net zero energy buildings are designed to operate at a higher performance level and therefore their systems are more finely tuned to match their passive design principles. For example, lighting power density is kept as low as possible in the net zero buildings due to their reliance on natural daylight to light the building. Artificial lighting is kept to a minimum. HVAC setpoints are generally set wider in net zero energy buildings in a bid to save energy. This must be balanced with the perceived comfort standard of occupants to ensure a comfortable environment indoors. Increasing the cooling setpoint from 24°C to 26°C at the Enterprise 1 building is predicted to result in a 25% energy saving, however this would not be feasible if occupants were not comfortable while in the building.

The effects of daylighting controls were modelled. It was found that significant benefits could be attributed to this where the building had high enough fenestration levels and its main occupancy was during the day. A simulated retrofit of daylighting controls to the Enterprise 1 building found that a 25% reduction in overall building energy use could be achieved. Simulations of the TTT and SBRC buildings show that daylighting controls contribute to savings of 21% and 8%, respectively. The low figure associated with the SBRC building is due to its open plan format relying heavily on natural lighting by-design. This anticipation in the design phase is the reason the SBRC building has such a low installed lighting power density compared to the other buildings and thus the reason daylighting has a significantly smaller benefit when compared to the other case study buildings.

The benefits of window shading in each building were examined. This is a complex design area and could not be fully investigated without significant changes to the envelope of each building. Instead, local shading of windows using high reflectivity slatted blinds was simulated. Results showed that the net benefit for all buildings was low. This was a result of an increased requirement for artificial lighting reducing any benefits that shading may have brought to HVAC loads. Different forms of shading would likely provide different results however, and further modelling of this would be worthwhile.

Higher performance glazing offers benefits for the net zero energy buildings where HVAC loads are dominant. Installing triple LowE glazing in these buildings offers a 6-11% reduction in overall use when compared to a benchmark of single glazed clear glass. For the Enterprise 1 building, where lighting and power loads are dominant, higher performance glazing upgrades have less effect on overall building energy use.

Triple LowE glazing offers only a 2% improvement in overall energy use compared to the single glazed benchmark.

Where HVAC loads are the dominant loads in the building, HVAC setpoint adjustment, installing higher performance glazing and, in some situations, window shading, can help to produce significant reductions in energy use. For buildings where HVAC loads are less significant, these changes will have less impact. More worthwhile changes in building design may be to install daylight controls.

# Chapter 6 Energy Balance & Grid Interaction of Case Study Building

For grid-connected net zero energy buildings, the interaction of electrical energy between the building and the grid is of importance and needs to be considered from the point of view of designing and maintaining grid infrastructure to cope with significant energy flows into the grid network that come with high penetrations of net zero buildings in the future. Energy storage such as batteries will help to address these issues with their ability to store and discharge energy at convenient and controllable times, however load matching and grid interaction factors must still be understood.

This chapter first presents an analysis of the energy balance of the SBRC building by the site and source energy metrics as outlined in Sections 2.2 and 2.3. Analyses of load matching and grid interaction issues for the SBRC building were also investigated.

## 6.1 Considerations in the calculation of building energy balance

Considering the key factors of net zero energy buildings as outlined in Sections 2.2 and 2.3, the balance calculations for the case study net zero energy buildings were performed. The key factors of balance metric and period must be first discussed to properly define the net zero energy building and its performance.

### *Balance metric*

The distinction between site energy and source energy is an important one when considering the balance metric. A site-energy metric considers only the energy consumed and generated, while a source metric considers the primary energy associated with the energy supplied from the grid. In an electricity grid with high penetration of fossil fuels, the primary energy factor is likely to be significant and may alter the operating outcome of the NZEB.

Australia’s electricity grid is dominated by fossil fuels. Approximately 87% of total generation in 2012-13 came from fossil fuels (refer to Figure 6-1), with the remaining 13% being sourced from renewables, mainly hydro [86].

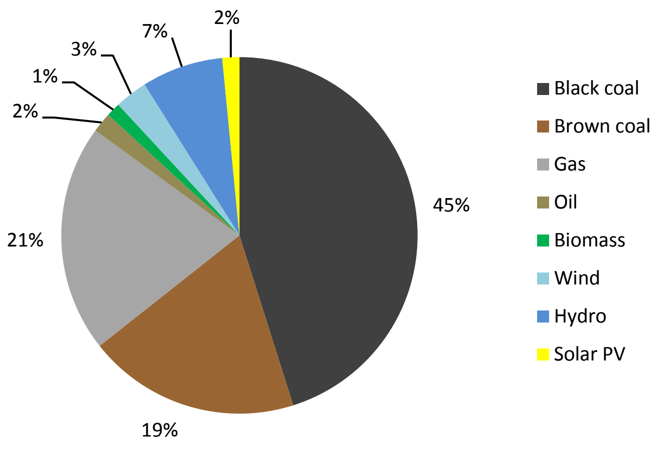


Figure 6-1 Australian electricity generation breakdown, 2012-13 [86].

To calculate the primary energy factor, it is necessary to determine the primary energy inputs used for electricity generation and compare this with overall electrical generation output.

$$Primary\ Energy\ Factor\ (PEF) = \frac{Primary\ energy\ inputs\ for\ electrical\ generation}{Electrical\ energy\ generated} \quad (6.1)$$

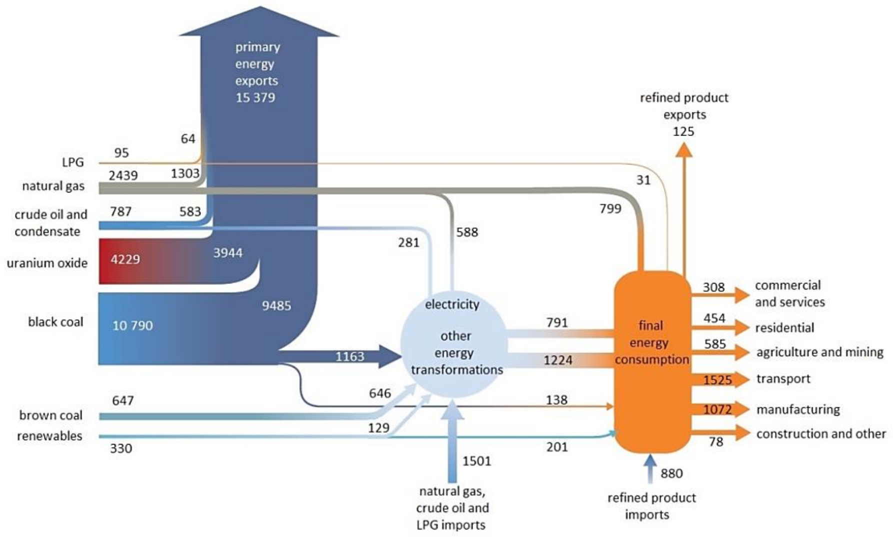


Figure 6-2 Australian energy flows, 2012-13[86].

From Figure 6-2 and *Table A-2, Australian energy supply and consumption* [86], the total primary energy inputs used for electricity generation in Australia for 2012-13 were 2,423.2 PJ. The resulting electrical energy generated was 791 PJ. Using equation (6-1), the Primary Energy Factor (PEF) for the Australian electrical grid for 2012-13 was calculated as 3.07. This value is not expected to vary significantly in the short term. This means that when determining the source energy balance for a NZEB, any unit of energy imported from the utility grid should be multiplied by 3.07 to properly account for the units of energy that were lost during electrical generation and transmission processes. Conversely, any unit of energy exported to the utility grid should also be multiplied by 3.07, as this counts as primary energy expenditure avoided.

#### *Balance period*

A NZEB with variable loads and generating capacity throughout the year may not achieve net zero energy on a short-term basis, but will make up for any deficits during other times. A year should be used as the balance period to allow for a full seasonal and operational cycle.

## 6.2 SBRC energy balance

Despite a loss of meter data occurring for the first half of the year 2015, manually recorded monthly readings enabled the site energy net zero balance to be calculated for the SBRC test case. Data from additional backup metering equipment implemented during 2015 could be analysed in such a way that the energy imported/exported balance was able to be determined for the purposes of calculating the source-energy net zero balance.

### 6.2.1 NZEB – Site energy

To illustrate the month-to-month behaviour of the building, Figure 6-3 shows the energy consumption, generation, and net balance for each month of 2015. Summer and spring months resulted in a net positive result averaging 13,000 kWh per month. This is due to the combination of these months providing the highest level of solar generation potential, as well as energy demand within the building being marginally lower than during winter – a result of more mild temperatures requiring less HVAC input. The net result during the winter and autumn months is still positive, however increased demand and lower solar yields resulted in an average net positive output of only 3,800 kWh per month.

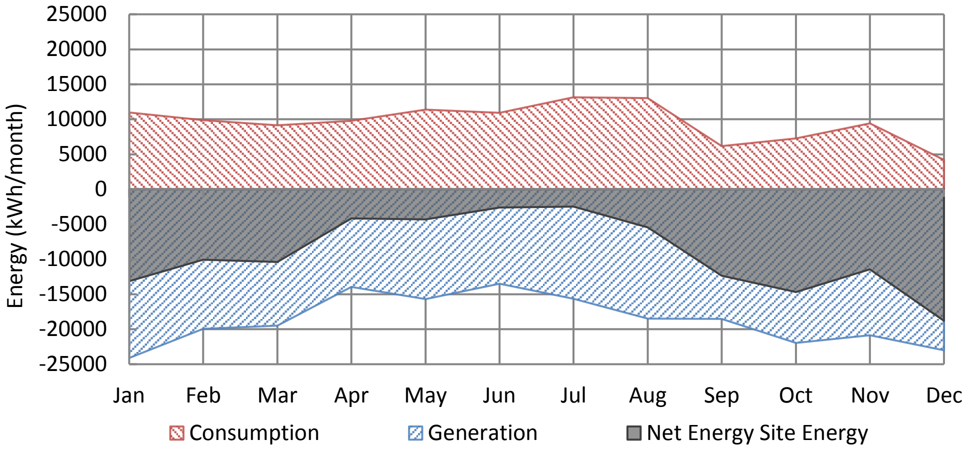


Figure 6-3 SBRC monthly site energy balance: 2015.

To better understand how the building tracks cumulatively throughout the year, Figure 6-4 shows the cumulative result of each month. The net balance at the end of 2015 was a positive result of 110 MWh.

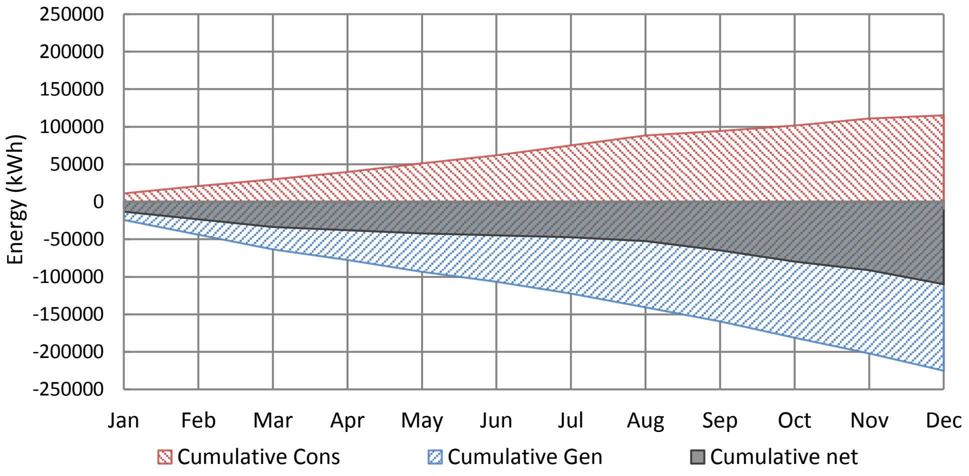


Figure 6-4 SBRC cumulative site energy balance: 2015.

The total generation for the year was 225,140 kWh, an average of 617 kWh per day. Total consumption was 115,240 kWh, averaging 316 kWh per day.

It must be noted that during 2015, the building was not operating at full occupancy capacity, nor were research labs and equipment fully fitted-out or installed. It is expected that energy consumption would increase in the future for these reasons. It is important to determine what the energy balance picture will be at full operating capacity. To project this, the energy consumption modelling provided by consultants performed during the design phase of the building was used. The recorded generation figure for 2015 will inform the other side of the equation. The consultants design figure for consumption was 164,016 kWh, an additional 48,776 kWh more than was recorded for 2015. Assuming annual generation of 225,140 kWh, the result is a net positive balance of 61,124 kWh.

### 6.2.2 NZEB – Source energy

To determine the net zero energy balance based on the source energy metric, it is necessary to determine the energy both exported and imported to and from the electrical grid. This differs from energy consumed and generated. The amount of energy consumed is not equal to the energy imported because some or all of the energy being consumed may be met by the building's own generating capacity at that time. For the same reason, the amount of energy generated differs from energy exported because some or all of the energy being generated is used to meet the building's own demand.

#### *Data analysis*

To determine the energy exported and imported, it may be possible to use the building's main incomer meters to separate these values. It would be a simple matter to read the imported and exported values on a monthly basis. For the SBRC building, it was made possible to do this in July of 2015. Prior to this time, it is possible to determine energy imported/exported by using historical power data if it is available. Separating the positive values (imported) and negative values (exported) of active power and numerically integrating them over the desired time periods will give figures for energy imported and exported for that time period.

Data collected using a Hioki power quality analyser on the main incomer from January to August of 2015 was used to calculate the monthly total imported and exported energy. This will be known as the *PQA integral method* presented in this chapter. From July onward, the data from the building BMS was used. The BMS logs a running total of the imported and exported energy values. Monthly totals were simply calculated from this. This will be known as the *BMS summation method*. To validate the effectiveness of these two methods of analysis and to ensure their results are comparable, overlapping data from the power quality analyser and the BMS was available for July. The *PQA integral* and *BMS summation* methods were compared. A third method was also used for validation. This is referred to as the *BMS integral method* and involves the same method used in the *PQA method* but with power data stored in the BMS being integrated.

### *PQA integral method*

This involves taking power (kW) data from the Hioki Power Quality Analyser in 10-minute time steps. The data is separated into values less than zero and values greater than or equal to zero. Positive values represent energy imported while negative values represent energy exported. This is illustrated in Figure 6-5 using data from a typical sunny winter day at the SBRC.

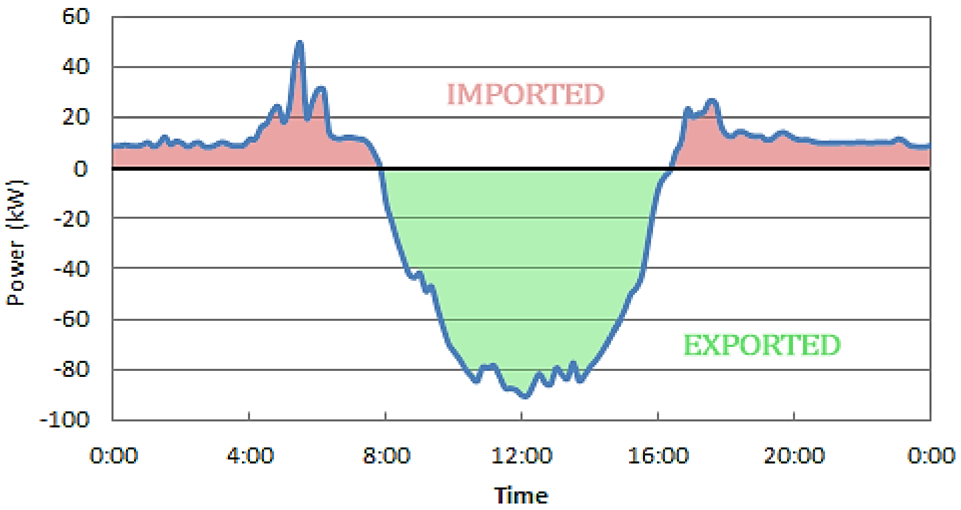


Figure 6-5 PQA integral method definition.

The separated data is then numerically integrated according to the appropriate time interval (10 minutes for the case of the PQA data). The total values for each month are then calculated and these become the energy imported and exported for that month.

Since readings took place only in 10 minute intervals, the values of power at each reading were average readings for that 10-minute duration. This means the data hides information related to rapid changes in power consumption and it is possible that rapid transitions between import and export have occurred. In this case, the detail would be lost through this method because only the net result in that time interval will be recorded. For example: if the meter reads 10 kW imported for 5 minutes and 10 kW exported for 5 minutes, then the resulting value that is recorded by the meter is 0 kW for that 10-minute time interval. This means that the 0.83 kWh of energy exported and 0.83 kWh of energy imported will not be counted when the power data is integrated. This is one benefit of using high resolution data in analysis such as this. However, it is not expected that error attributed to this phenomenon will have a significant impact on the final result.

The *BMS integral method* is exactly the same as that used in the *PQA method*, the only difference being that the BMS data time interval is 15 minutes instead of 10 minutes.

### Validation of methods

For the source energy metric, the data from two different methods was used, and it was necessary to ensure that the data and their analysis techniques are comparable. Fortunately, the data from July overlapped and thus can be compared for an entire month. Figure 6-6 shows a comparison of the power data from the Hioki PQA, with power data from the BMS for a day in July. It was observed that both sets of data matched well with each other, albeit with a slight difference in timing.

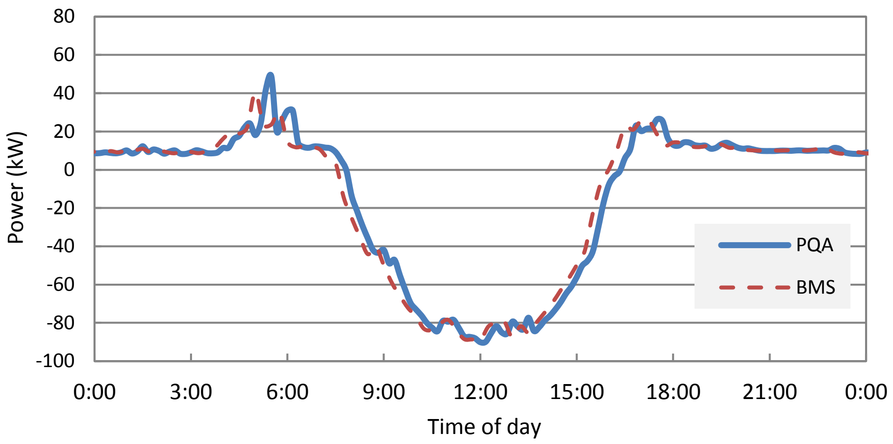


Figure 6-6 Power profile comparison as measured by BMS & PQA: 5/07/2015.

Since it is established that the raw power data is a satisfactory match, the methods of analysis may be compared. The *PQA integral method*, *BMS integral method*, and *BMS summation* methods were all performed for the month of July, the result being a figure for total energy imported and exported for each method. The results are shown in Figure 6-7.

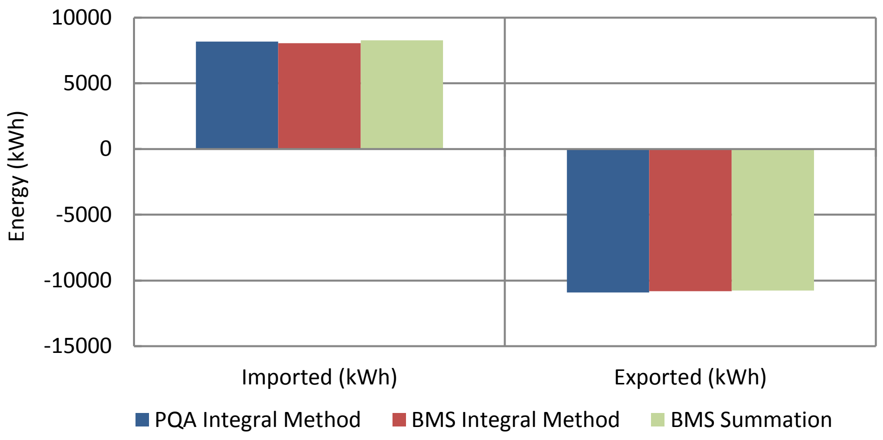


Figure 6-7 Comparison of imported/exported calculation methodologies.

Numerical values are recorded in Table 6-1 along with their relative errors compared to the *PQA integral method*. A maximum error of 1.5% is recorded for the month of July. This indicates that the methods used to determine imported and exported energy from the SBRC on a monthly basis are sufficiently accurate as to provide confidence in the SBRC buildings net zero energy source metric results.

Table 6-1 Comparison of errors for imported/exported calculation methodologies.

| | Imported (kWh) | Exported (kWh) |
|---|---|---|
| **PQA Integral Method** | 8169.38 | -10917.15 |
| **BMS Integral Method** | 8047.22 | -10815.80 |
| **BMS Separated Summation** | 8269.80 | -10765.20 |
| **PQA Integral Method** | - | - |
| **BMS Integral Method** | 1.50% | 0.93% |
| **BMS Separated Summation** | -1.23% | 1.39% |

Figure 6-8 shows the energy consumption, generation, and net balance for each month of 2015 according to the source metric. These results confirm that the building makes an even more valuable contribution to decarbonizing of the built environment than in the site metric due to the surplus energy it produces which avoids consumption of fossil fuel generated grid electricity.

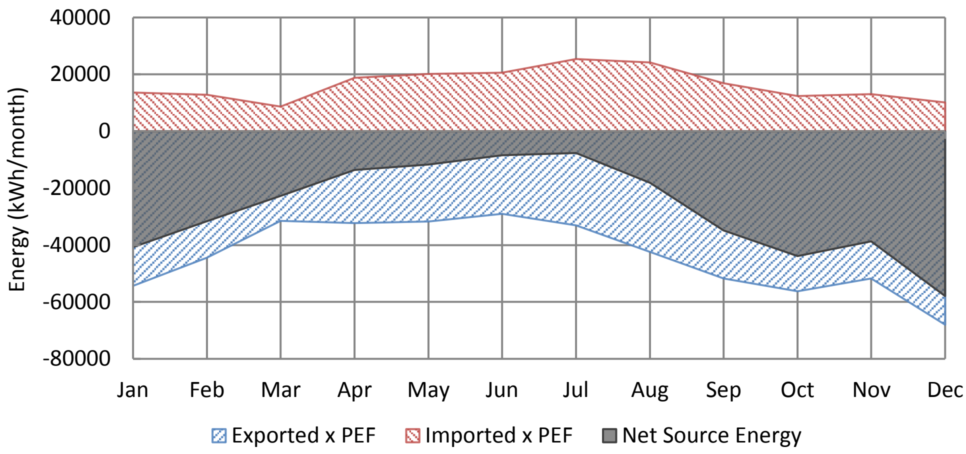


Figure 6-8 SBRC monthly source energy balance: 2015.

The primary energy factor (PEF) of 3.07 as discussed in Section 6.1 is applied on both sides of the energy equation. Whilst this increases the primary energy associated with imported energy, it also increases the primary energy consumption that is avoided thanks to the export of surplus energy. Exported energy from the SBRC building is used by other buildings on the same campus and thus saved them importing energy from the grid with the 3.07 primary energy factor.

The cumulative source energy balance for 2015 is shown below in Figure 6-9.

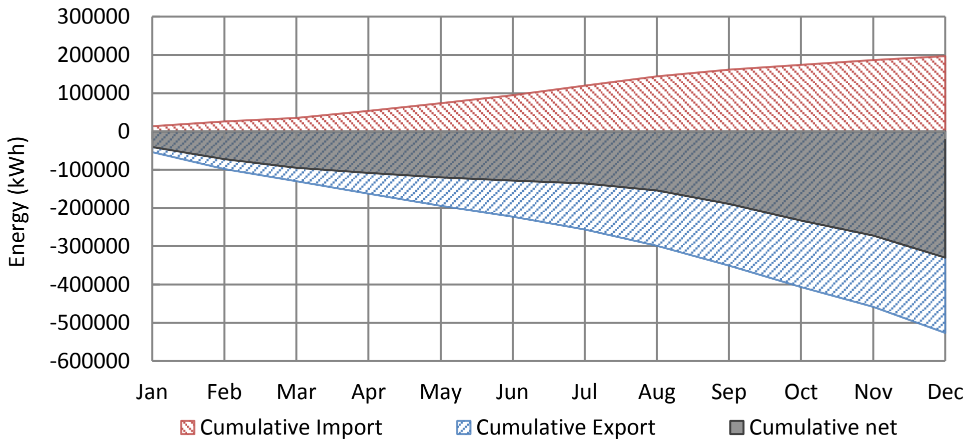


Figure 6-9 SBRC cumulative source energy balance: 2015.

The total energy imported from the grid for the year was 197,708 kWh, an average of 541 kWh per day. Total energy exported to the grid was 526,517 kWh, averaging 1,443 kWh per day. The surplus of primary energy at the end of 2015 was 330 MWh.

A comparison of the cumulative net energy balance throughout the year for the site and source metrics is shown in Figure 6-10. When the source metric is considered, the

SBRC is three times more effective as a net zero energy building than when the site metric is employed. This is expected given the PEF is 3.07.

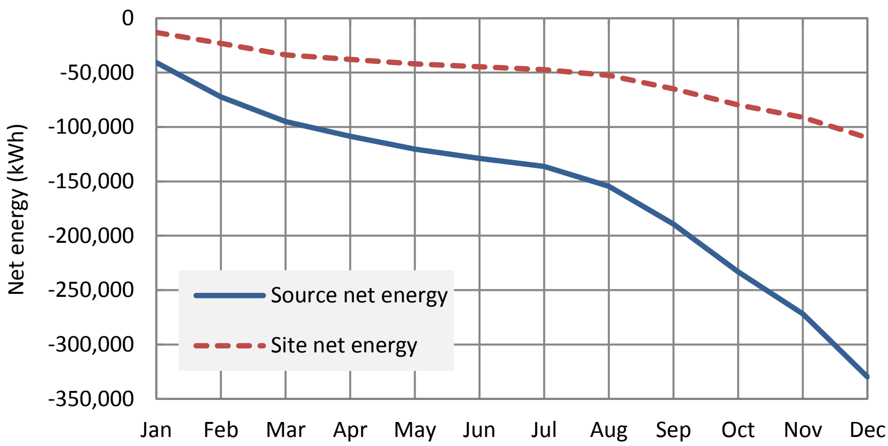


Figure 6-10 SBRC net zero energy balance metric comparison: 2015.

## 6.3 Load-matching & grid interaction considerations for the SBRC

As has been discussed in Section 2.6.2, the major difference between conventional electrical supply and on-site renewable energy is that renewables are a variable resource. This means that a constant reliable renewable supply is not always possible to maintain and thus variations in output occur throughout the day, and in the case of rooftop solar PV, over longer seasonal periods (average summer solar PV output is approximately 40% higher than average winter output as recorded by the data in Section 6.2.1). The ideal situation is that the generation profile is matched to the buildings' load profile and for many commercial buildings this will be case for a significant percentage of the time, but far from 100%. Additionally, with more and more buildings having solar PV installed on site, future large export events are likely to occur on sunny days when all buildings in the area are producing surplus energy and are exporting to the grid. The potential for grid stability issues caused by these two-way energy transfers between the grid and buildings must be considered if net zero energy buildings are to become commonplace.

### 6.3.1 Load match index

To measure the degree to which the energy generated by the building is able to meet the load of the building at any particular time, the load match index (LMI) is used [55]. The LMI over a given time period is defined as the mean of the ratio between generation and load for each time step. Where the generation exceeds the load, the LMI for that time step is equal to one. The LMI will never be more than one. This is because it is simply a measure of how well the present load is met by on-site renewable generation at that time. If the generation output is more than or equal to the load, the load is being met 100% by generation, regardless of how much it exceeds the magnitude of the load.

The LMI is affected by the time interval of data used. For a net zero or net positive building, the LMI will be equal to one when viewing its annual energy balance. However, on shorter timescales, the generation will not always match the load. On a daily basis, with only solar PV and without storage, the generation will not match load as generation is not possible outside of sunlight hours. This means that the LMI will be less than one. To ensure a more accurate LMI, high resolution data should be used [54]. For this study, the data time interval used was 15 minutes. Ideally a full year of 15-minute data would be available however, in this case, only data from July to the end of 2015 was available. This will still give a good indication of the overall average LMI for the year as summer and winter seasons are still well represented in the data. An average representative day of generation and load at the SBRC building is shown below in Figure 6-11. One aspect to note is the early morning peak in the consumption profile. This is caused by early morning pre-heating and cooling of the concrete hydronic slab system, particularly in winter.

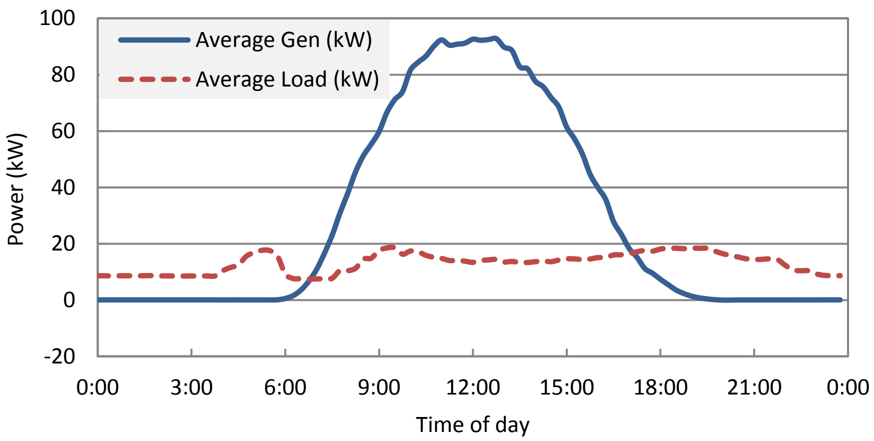


Figure 6-11 SBRC average load and generation profiles: 2015.

Visual inspection of the chart indicates that the load is matched (remembering the surplus is ignored when considering the LMI) roughly 40 to 50% of the entire day. The relatively flat load profile of the building makes the visual estimate of the LMI simple.

Using the 15-minute data from July to the end of December the LMI is described as follows:

The ratio between generation and load is calculated for each data point:

$$LMI_i = \min\left(1, \frac{P_{gen,i}}{P_{load,i}}\right) \tag{6.2}$$

Where *i* is the value at each time step, $P_{gen}$ is the generation power output for a given time and $P_{load}$ is the load at the given time. This is the simplest form of the LMI equation, where storage and any system losses are ignored.
This is calculated for every *n* time-step in the data set. The mean of the LMI for all data points is then calculated to give the LMI for the time period considered:

$$LMI = \overline{\sum_{\iota=1}^{n} LMI} \tag{6.3}$$

For the SBRC building, using the data available, the average LMI for the six-month period July to December was calculated to be 43.5%. The average LMI for the average 24-hour period shown in Figure 6-11 (averaged from the same July to December data) is 47.9%.  This agrees well with the visual estimate made above.

The result means that the SBRC building, despite being a net positive building throughout the year on a yearly, monthly, and frequently daily basis, is only able to meet its own energy requirements 44% of the time when sub-hourly data is considered due to overnight loads being unable to be matched with solar PV output which of course cannot generate at night.

General suggestions for improving the LMI are to implement demand-side management (DSM) strategies, as well as increase generation capacity. In the specific case of the SBRC building, increasing generating capacity will not improve the situation, given that the problem lies not in the output potential, but in the output timing. DSM, too, is unlikely to have a significant effect on the LMI, given that the load profile of the building is typically quite flat across the day.

One strategy which may improve the LMI is not to increase solar PV generating potential, but to diversify the generation techniques. Installation of small-scale wind turbines on the site could generate energy during the night where solar PV cannot. However, this improvement would be intermittent, depending on the quality of the variable wind resource at the site. The most promising method of improving the LMI at the SBRC is to install battery storage. A large surplus is generated every day by the solar PV system, excluding days of inclement weather. A battery storage system sized to match the average or peak magnitude of overnight energy requirements would be charged during the day at times of surplus generation and would discharge overnight when the load exceeds generation.

### 6.3.2 Grid interaction index

Whilst the load match index measures the degree to which the generation of the building is able to meet its load requirements, the grid interaction index (GII) measures the variability of energy exchange with the grid over a particular time period. It is a comparison of the net grid energy reading to the maximum value of net energy in the time period. The GII explains the variability of energy exchanged with the grid by taking the standard deviation of the GII for each time step of the time period. It is not related to the magnitude of electricity required from the grid. The GII is calculated as follows:

The net power reading of the main incomer at each time step is compared to the maximum of the absolute value of net power in the dataset:

$$GII_i = \frac{P_{net,i}}{max|P_{net,n}|} \tag{6.4}$$

Where $i$ is the value at each time step, and $P_{net}$ is the power reading at the main incomer of the building.

$GII_i$ is calculated for every $n$ time step in the data set. The standard deviation of the $GII_i$ dataset is then calculated to give the average grid stress for the time period considered:

$$GII_n = STD(GII_i) \tag{6.5}$$

For the case study SBRC building, the GII for the year was calculated to be 0.22. Whilst there is not yet a large volume of NZEBs reporting their GII's in the literature, this result is a good comparison with the small number of results reported for GII in [54].

### 6.3.3 Power quality considerations of net zero energy buildings

Net zero energy buildings typically utilise a range of high efficiency appliances, such as lighting equipment. The impact of such equipment from the perspective of power quality and the consequences for the grid needs to be considered. Whilst a detailed analysis of these factors in relation to NZEBs is beyond the scope of this thesis, some preliminary presentation of basic power quality data is provided here.

*Power Factor*

The first consideration for power quality in commercial buildings is often power factor. Power factor is the ratio of real power (kW) to apparent power (kVA). While optimising power factor, i.e. making it closer to unity, will have little effect on the energy use internally within a net zero energy building, utilities provide incentive to increase power factor through penalties for exceeding minimum power factors and indirectly via demand charges (which are a function of apparent power). Accordingly, commercial buildings will generally have a power factor correction unit, typically a large switched capacitor bank, installed to increase power factor during high reactive power (kVAr) demand periods.

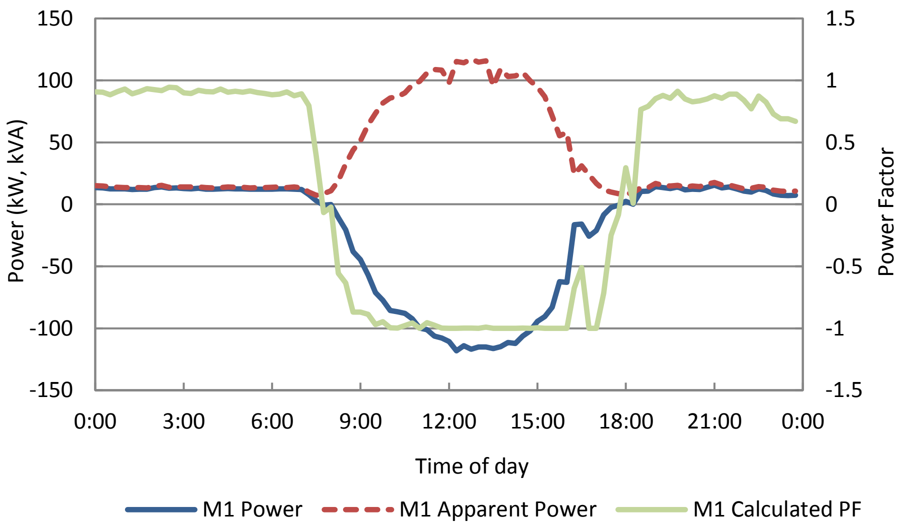


Figure 6-12 SBRC 15-minute average power factor, real, and apparent power.

From Figure 6-12 it can be seen that the nominal power factor of the SBRC is close to unity during both generation and non-generation periods. Note that M1 refers to the meter number installed on the main incomer of the SBRC building. This is proposed to be largely due to the combined power factor of high efficiency equipment such as LED lighting, inverter based variable speed drives, etc., which will be synonymous with net zero energy buildings or buildings retrofitted for energy efficiency improvements. The power factor of such equipment at the SBRC has negated the need for costly power factor correction equipment to be installed. It is noted that in Australia, at present, generation from the solar photovoltaic system inverters are required to deliver power to the local load and grid at near unity power factor.

### *Harmonics*

The operation of modern, high efficiency lighting technology produces significant harmonic distortion in the currents that they draw from the power system. While harmonic distortion levels are often factored into equipment standards to reduce their impact on the grid, the high penetration of such devices in the low voltage distribution system of net zero energy buildings needs to be understood. While power quality analysis is beyond the primary scope of this thesis, some preliminary reporting on the harmonic distortion levels, available from the installed sub metering equipment, is presented here as a prelude to possible future research. Figure 6-13 shows that there is a high level of harmonic distortion in the current drawn from the grid by the SBRC.

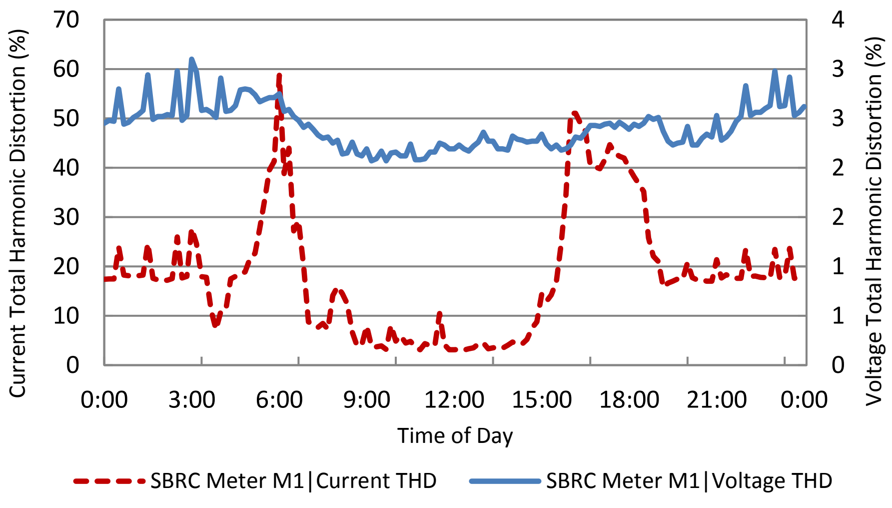


Figure 6-13 SBRC THD of voltage and current on a typical day.

The resulting harmonic distortion in the voltage is within acceptable limits [87] however consideration of harmonics needs to be factored into the design of the electrical system (rating of cables, etc.). It is also noted that operation of the solar photovoltaic system inverters, i.e. in times of generation, reduces the levels of current and voltage harmonic distortion on the system.

### *Voltage Rise*

Voltage rise due to localised generation within the network is also another important consideration for net zero buildings. At the SBRC, several instances of voltage greater than the recommended limits have been recorded where the photovoltaic inverters connect into the electrical distribution systems. Figure 6-14 illustrates the voltage level recorded at the inverter connection and main switchboard at an example high generation period. The maximum allowable voltage of 253 $V_{rms}$ is exceeded for some periods of time at the inverter connection. At the SBRC only the connected inverters see these higher voltages, however if more sensitive equipment was connected at the same point, reduction in equipment lifetime is possible.

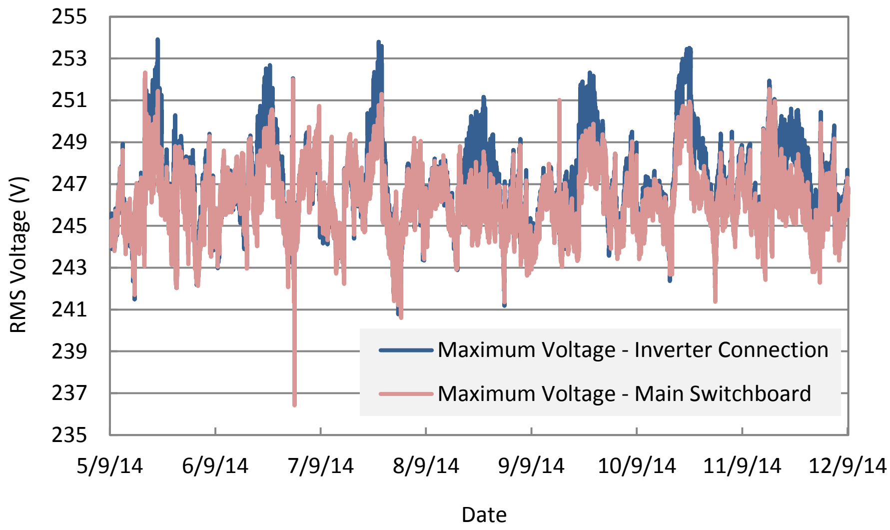


Figure 6-14 Maximum RMS voltage levels at the SBRC.

## 6.4 Summary

This chapter reported on the energy status of one case study net zero energy building, the Sustainable Buildings Research Centre, as well as factors relating to load match and grid interaction. Results have shown that the SBRC building is a successful net positive energy building, producing an annual surplus of 110 MWh and remaining net zero for every month of the year. When the primary energy on the utility grid is considered, the success of the building triples due to its large surplus being able to avoid primary energy expenditure for the surrounding buildings. Whilst the building is not yet fully equipped or occupied, modelling of consumption using figures provided by the building design consultants indicate that the building will still easily achieve net zero when fully occupied.

An analysis of how the SBRC building is able to match its generation and load profiles, and how it interacts with the grid was also performed. The reported Load Match Index was found to be 43.5% for the second half of 2015. The GII for 2015 was found to be 0.22. It is desirable for the GII to be as low as possible. Electrical equipment must be designed for peak loading. Significant infrastructure savings can be found in reducing the expected peak loads in a system. The LMI, together with the GII provide a means to quantify how the building interacts with the utility grid. Peak import and export events can be reduced through implementation of load matching improvement measures to minimise interaction of the building with the grid. A high GII means the building has a highly variable relationship with the grid, ranging from high levels of import or export to having little interaction at all. Since infrastructure is designed for extreme cases which may happen only on very rare occasions, reduction of grid interaction variability can save significant costs by lowering the levels with which infrastructure must cope.

While energy generation and use is of primary importance to NZEB design, other considerations associated with the energy delivery system need to be included during design, e.g. power factor and power quality requirements. While such considerations are relevant to all buildings, the uniqueness of NZEBs means that power factor correction equipment may be omitted in some cases, and the electrical distribution system needs to be able to mitigate the harmonics of high energy efficiency equipment as well as voltage rise from localised generation.

# Chapter 7 Conclusion and Future Work

As a promising design philosophy in the future of the built environment, the success of net zero energy buildings depends greatly on a good understanding of the influence that different design factors have on the energy performance of a building. The importance of design and operational factors to the success of net zero energy buildings has been investigated through the use of building performance simulation. This research entailed the development of building performance models for three case study buildings as well as a comprehensive validation methodology for each model.

## 7.1 Building model validation

This thesis demonstrated that validation of models of efficient buildings is more challenging than models of conventional buildings due to intelligent systems which are able to adjust their behaviour automatically depending on a range of environmental variables such as available natural light. This has the effect of making energy consumption of these systems more variable than in a conventional building and thus more difficult to model where provision of specific environmental inputs is not made. Natural ventilation in building models is not as easily predicted as behaviour of artificial HVAC systems. More complex modelling techniques which consider the intricacies of internal and external airflow interactions with the building envelope would possibly provide more accurate results.

A methodology to successfully validate building models and simulation results was developed. Successful validation of building models is dictated heavily by the availability and reliability of measured building data. Both energy consumption for the main building systems (HVAC, lighting, building services), as well as temperature data for summer and winter periods for several zones within the building, are recommended to ensure the building not only exhibits characteristic energy consumption behaviour, but that the building responds properly in a thermal respect. One challenge encountered in this study was obtaining adequate data for all test cases. No thermal data was available for the Enterprise 1 building, while very little energy data was obtainable from the TTT building. Had a longer timeframe been available for data acquisition, a better result may have been achieved regarding the validation of the case study building models. Nonetheless, the modelling performed here can be regarded as adequate, given that results are compared to a benchmark of the same building model for each scenario.

## 7.2 Building simulation results

Simulations were undertaken to investigate the performance of net zero energy buildings. The effectiveness of various designs and operating parameters were modelled to gain an understanding of the most effective way of reducing energy consumption and achieving net zero energy in a building. The net zero energy case study buildings studied here indicated from simulation results that efficient buildings are more sensitive to changes in design or operating practices than more conventional buildings. This suggests that a building designed from scratch for the purpose of being net zero will have the best chance of achieving that goal. A retrofitted building may not achieve this goal as easily due to factors such as the building envelope not being designed to be able to capture the maximum amount of daylight to aid in reducing lighting loads. Another factor which may affect the outcome of a retrofitted building compared to a NZEB designed from scratch is that the building layout may not lend itself to successful natural ventilation implementation. Ideally a building with a successful natural ventilation scheme will be designed with cross-flow of air in mind: open plan spaces with large atrium common areas enabling airflow between different levels of the building. Buildings should be narrow to maintain sufficient air distribution throughout the interior.

The research undertaken in this thesis indicated that significant benefits to energy consumption are possible with the installation of high performance glazing. Energy savings between 6% and 11% are possible in net zero buildings when triple glazed, low emissivity glass is used compared to a benchmark of single glazed, clear glass. Higher performance glazing presented less of a benefit for the conventional building due to HVAC loads (the aspect most effected by glazing) being less dominant than in the NZEBs.

Simulations of building models and complimentary data collection from case study buildings have shown that controlling lighting output in proportion to the available amount of daylight present in a room also presents significant benefits to energy reduction in buildings. Large open plan spaces with high levels of external and internal glazing benefit most from this, enabling maximum transmission and penetration of natural light into the building. This is where design intent is important and where older, more conventional buildings may not achieve benefits. Enterprise 1, the conventional building studied here, was designed with open plan offices, as well as large atriums with skylights at each end of the building. This makes it a very good candidate for the retrofitting of daylighting controls. Simulation results suggested an overall saving of 25% to total building energy use. This is a significant saving due as lighting is one of the most dominant loads in this building. In the TTT building, an overall saving of 21% was determined compared to a scenario where daylight controls were not installed, while at the SBRC, it was found that due to the already very low lighting power density specified in the design phase, daylight controls contribute to only an 8% energy saving.

The implications for energy consumption from window shading controlled by both time of day and outdoor temperature were investigated. Overall, the net benefit to total energy consumption in each building was insignificant, if there was a benefit at all. Typically, any improvement due to reduction in HVAC loads was cancelled out by the need for significant increases in lighting use to compensate for lost daylight.

From simulations performed on the case study building models, adjustments of HVAC setpoint offer meaningful energy savings. Net zero buildings appear most sensitive to changes in HVAC setpoints but it must be considered that the default setpoints are wider than usual to begin with. It is important that any changes to HVAC setpoints must meet the perceived comfort standard of occupants to ensure a comfortable environment indoors. Increasing the cooling setpoint from 24°C to 26°C at the Enterprise 1 building was predicted to result in a 25% energy saving, however this would not be feasible if occupants were not comfortable while in the building.

## 7.3 Energy balance & grid considerations of case study NZEB

Analysis of a full year of data available for the Sustainable Buildings Research Centre building has enabled the net zero status of the building for 2015 to be established. The position of the SBRC was successful, generating an annual energy surplus of 110 MWh and maintaining a surplus throughout every month of 2015 based on the site energy metric (a comparison of energy consumed to energy generated). The analysis included consideration of the primary energy factor of the utility grid, calculated in order to assess the source energy balance (a comparison of energy imported to energy exported). With a primary energy factor of 3.07 established based on the most recent data available, the source energy balance for the SBRC improved the contribution of the building to emissions reduction by a factor of three. The large surplus of energy produced is used elsewhere on the campus, thereby avoiding the expense of primary energy associated with imports from the utility grid.

Analysis of the load match and grid interaction factors at the SBRC provided an indication of what possible challenges high numbers of NZEBs will present to the utility grid in the future. Maximising the ability for the building to cover all of its own loads with on-site generation at all times of the day, as well as minimising the variance of energy transfer between the grid and building is important to reduce grid infrastructure capital and maintenance costs. The Load Match index for the SBRC based on available data of 15-minute intervals was calculated to be 43.5%. The Grid Interaction Index was calculated to be 0.22. With the increasing affordability of battery storage, this technology makes the prospects of improving the Load Match Index much easier. Surplus energy generated during the day is stored for overnight use. Additionally, diversification of on-site renewable technology through the addition of small-scale wind turbines would also serve to improve the Load Match Index.

The balance of energy generated and consumed is of primary importance to the field of net zero energy buildings; however, considerations must be made regarding power quality. Primarily the power factor, total harmonic distortion, and voltage rise must be considered in the design phase of buildings. The general overview and brief analysis of these factors for the SBRC case study suggest that power factor correction equipment may not be necessary in some cases.

## 7.4 Suggested future research

Upon the fulfilment of the aim and objectives of this thesis, several areas of potential research have been identified:

- Further efforts to more comprehensively validate each building model using a complete year of temperature and energy data. This would improve the confidence of the results of this thesis, and also enable further study in other areas of building research using robust and reliable building model case studies.

- Whilst the effects of window shading on energy consumption for the three test cases were simulated, the subject of shading elements in buildings is a broad one and should consider many interrelated variables. This made the study of this field, using differing case study buildings, difficult given that each building has its own location and building-specific shading elements already built-in. Further understanding of the effects of building shading elements on energy consumption would be gained through a separate study using a hypothetical model on which to investigate such factors as roof and window overhangs, vertical wall and window fins, and the placement of surrounding features such as buildings and vegetation. The 'all-or-nothing' approach to window shading modelling performed in this study led to poor results. However, investigation of more nuanced and subtle shading devices may find a positive and significant effect on energy consumption.

- Important questions regarding occupant interaction with buildings and their effects on energy consumption were raised in this thesis. However, the modelling methodology employed did not lend itself to the study of occupant behaviour. One potential area of research in this field would be how energy consumption and efficiency initiatives shape the behaviour of occupants in a building and whether these initiatives conflict with occupant needs and preferences. It is suggested that net zero energy buildings will be more successful if their occupants embody a culture of energy conservation, however this would warrant further investigation. A successful NZEB would be one which requires little habitual and cultural change from its occupants as this may present a barrier to widespread up-take.

- This study focussed on the modelling of three case study buildings conveniently situated in close proximity to each other. This made validation of each model simpler and the results were able to be compared on a level basis. However, the three buildings had differing sizes and purposes. These two factors are likely to affect energy consumption and thus some conclusions made here may not be able to be applied more broadly to buildings in general with total confidence.

More work should be undertaken with a higher sample size of case study buildings, both NZEB and conventional, in order to build up a reliable picture of factors which drive energy savings in NZEBs and how they compare to conventional buildings.

- A brief overview of the power quality factors which warrant consideration in the design of a NZEB was given in this thesis. This is a field where deeper research is necessary to understand how large numbers of net zero buildings interact fully with the grid and what implications this may have in the field of power quality.

# Appendices

## Appendix A. $R^2$ plots omitted from Section 4.4.2

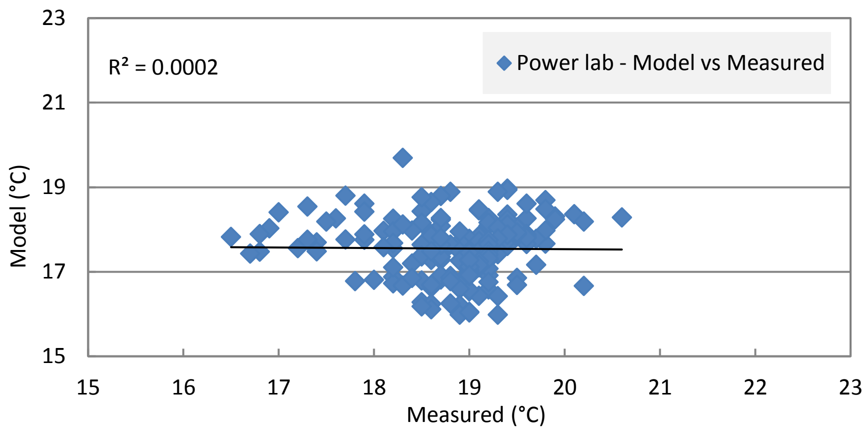


Figure A-1 $R^2$ for SBRC energy lab room temperature comparison - winter

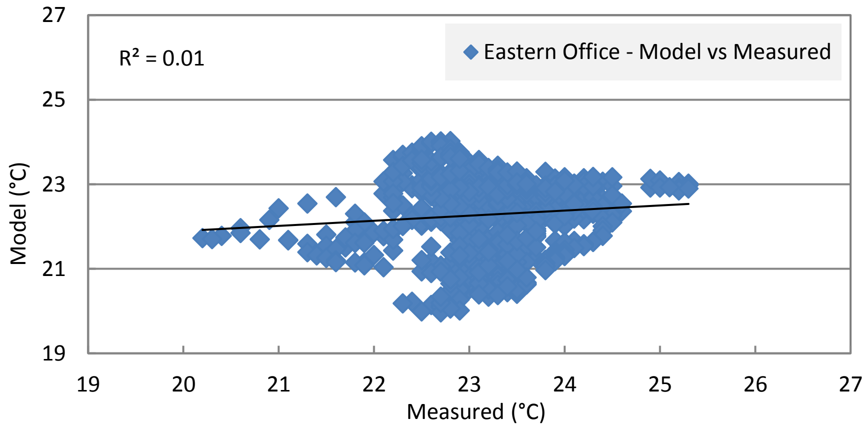


Figure A-2 $R^2$ for SBRC Eastern Office temperature comparison - summer

# Appendix B. Tables and Figures Omitted From Chapter 2

The following tables and figures relate to literature sources that form sections of the literature review in Chapter 2. The sources these figures were taken from shape the conclusions made in the literature review, but the figures themselves were not deemed integral to the understanding of the conclusions. They are provided here with citation to provide the reader a deeper understanding if desired.

Figure B-3 from Belleri et al. [17] is an example of the output of the Excel tool showing the NZEB balance for three differing NZEB definitions, as well as the monthly tracking of energy use and generation for the case study building.

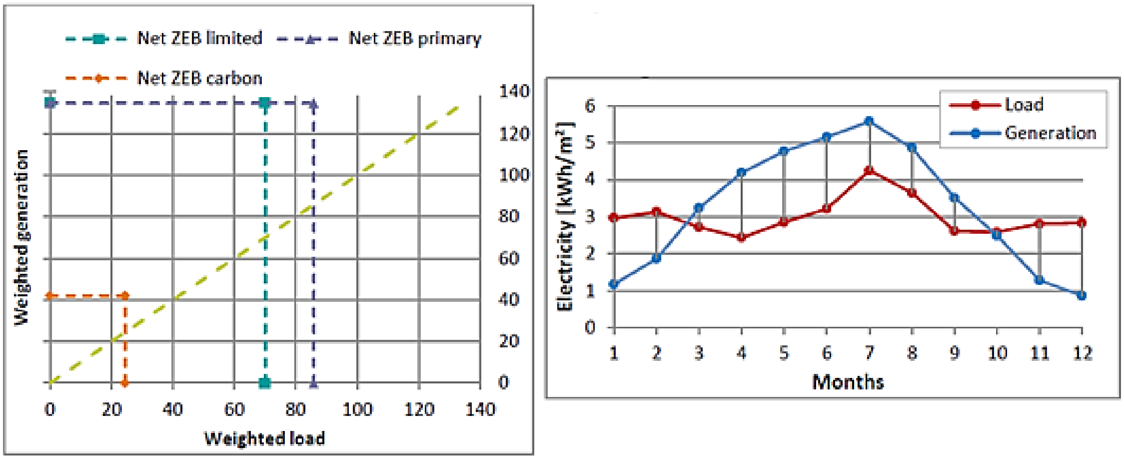


Figure B-3 NZEB balance for three definitions; Tracking of load/gen. - [17].

Results of the study by Nguyen & Altan [28] according to the prescribed criteria are shown below in Table B-1.

Table B-1 Results from [28].

| | BREEAM | LEED | CASBEE | GREEN STAR | HK-BEAM |
|---|---|---|---|---|---|
| Popularity and Influence | 10 | 10 | 6 | 5 | 5 |
| Availability | 7 | 7 | 7 | 8 | 8 |
| Methodology | 11 | 10 | 13 | 9 | 11 |
| Applicability | 13 | 13 | 11.5 | 10 | 9 |
| Data Collecting Process | 7 | 7 | 6 | 9 | 8 |
| Accuracy and Verification | 8 | 7 | 9 | 5 | 5 |
| User-friendliness | 8 | 10 | 6 | 8 | 8 |
| Development | 8 | 8 | 7 | 8 | 8 |
| Results Presentation | 3 | 3 | 4 | 3 | 4 |
| Final Score (/100) | 75 | 75 | 69.5 | 65 | 66 |

Table B-2 is an excerpt from Dubois & Blomsterberg [38] showing the type of energy saving strategy and it's potential for savings.

Table B-2 Energy savings potential of different strategies by [38].

Overview of energy saving strategies and relative energy saving potential.

| | Energy saving strategy | Relative saving potential |
|---|---|---|
| 1 | Improvement in lamp technology | 10% (T12 to T8) 40%[a] (T12 to T5) |
| 2 | Improvement in ballast technology | 4–8% |
| 3 | Improvement in luminaire technology | 40%[b] |
| 4 | Use of task/ambient lighting | 22–25% |
| 5 | Improvement in maintenance factor | 5%[c] |
| 6 | Improvement in utilization factor | Depends on application and context |
| 7 | Reduction of maintained illuminance levels | 20% (500 to 400 lx) |
| 8 | Reduction of total switch-on time | 6%[d] |
| 9 | Use of manual dimming | 7–25% |
| 10 | Use of switch-off occupancy sensors | 20–35% |
| 11 | Use of daylight dimming | 25–60%[e] |

# Appendix C. Data Sets

All data sets relating to building models, measured building data, simulation results, and weather files are stored in the Sustainable Buildings Research Centre data repository and are available upon request to the author or to the SBRC directly. A list of available files is given below:

Table C-3 List of available data related to this thesis

| File No. | File Name | File Type | Relating to: |
|---|---|---|---|
| 1 | SBRC Monthly Energy Balance | .xlsx | SBRC |
| 2 | Model EUB's | .xlsx | ALL |
| 3 | SBRC – DRAFT Building Users Guide | .pdf | SBRC |
| 4 | 1004305 Uni of Wollongong_SBRC_TEC Report – Rev C | .pdf | SBRC |
| 5 | SBRC MECH Drawings | .pdf | SBRC |
| 6 | SBRC ELEC Drawings | .pdf | SBRC |
| 7 | WSP Mechanical Services Specification | .pdf | SBRC |
| 8 | TTT ARCH Drawings | .pdf | TTT |
| 9 | TTT MECH Drawings | .pdf | TTT |
| 10 | TTT ELEC Drawings | .pdf | TTT |
| 11 | AC 1 Energy report Jan to April 15 | .pdf | TTT |
| 12 | AC 2 Energy report Jan to April 15 | .pdf | TTT |
| 13 | AC 3 Energy report Jan to April 15 | .pdf | TTT |
| 14 | Level 1 lighting year to date | .xlsx | TTT |
| 15 | Level 1 power year to date | .xlsx | TTT |
| 16 | Level O lighting year to date | .xlsx | TTT |
| 17 | RRSB year to date | .xlsx | TTT |
| 18 | TTT Energy Data | .xlsx | TTT |
| 19 | Yea to date level O power | .xlsx | TTT |
| 20 | Water Furnace Specs | .pdf | TTT |
| 21 | Enterprise 1 ARCH Drawings | .pdf | E1 |
| 22 | Asset List & Synthetic Breakdown | .pdf | E1 |
| 23 | Enterprise-1 Manual | .pdf | E1 |
| 24 | iCE1 Volume 1 Building Works | .pdf | E1 |
| 25 | Lighting Sheets | .pdf | E1 |

| | | | |
|---|---|---|---|
| 26 | DesignBuilder TTT | .zip | TTT |
| 27 | DesignBuilder SBRC | .zip | SBRC |
| 28 | DesignBuilder Enterprise One | .zip | E1 |
| 29 | BMS Data | .zip | SBRC |
| 30 | Aust electrical breakdown | .xlsx | ALL |
| 31 | Bellambi TMY DB temp histogram | .xlsx | ALL |
| 32 | SBRC Incomer HIOKI Power Data 2015 02-01-15 to 31-07-16 –chapter 6 | .xlsx | SBRC |
| 33 | Glazing Simulations | .xlsx | ALL |
| 34 | Glazing simulations_Identical lighting system | .xlsx | ALL |
| 35 | Glazing simulations_Identical lighting system_no control | .xlsx | ALL |
| 36 | HVAC SP analysis | .xlsx | ALL |
| 37 | Lighting Control simulations | .xlsx | ALL |
| 38 | Shading analysis | .xlsx | ALL |

# References

[1] L. Guan, “Energy use, indoor temperature and possible adaptation strategies for air-conditioned office buildings in face of global warming,” *Building and Environment*, vol. 55, pp. 8–19, Sep. 2012.

[2] X. Wang, D. Chen, and Z. Ren, “Assessment of climate change impact on residential building heating and cooling energy requirement in Australia,” *Building and Environment*, vol. 45, no. 7, pp. 1663–1682, Jul. 2010.

[3] International Living Future Institute, “Living Building Challenge,” 2015. [Online]. Available: http://living-future.org/lbc. [Accessed: 04-Apr-2016].

[4] D. H. W. Li, L. Yang, and J. C. Lam, “Zero energy buildings and sustainable development implications – A review,” *Energy*, vol. 54, pp. 1–10, Jun. 2013.

[5] L. Pérez-Lombard, J. Ortiz, and C. Pout, “A review on buildings energy consumption information,” *Energy and Buildings*, vol. 40, no. 3, pp. 394–398, Jan. 2008.

[6] International Energy Agency, “World Energy Outlook,” Paris, 2013.

[7] P. de Wilde and D. Coley, “The implications of a changing climate for buildings,” *Building and Environment*, vol. 55, pp. 1–7, Sep. 2012.

[8] Z. Ren, Z. Chen, and X. Wang, “Climate change adaptation pathways for Australian residential buildings,” *Building and Environment*, vol. 46, no. 11, pp. 2398–2412, Nov. 2011.

[9] P. Wilkinson, K. R. Smith, M. Davies, H. Adair, B. G. Armstrong, M. Barrett, N. Bruce, A. Haines, I. Hamilton, T. Oreszczyn, I. Ridley, C. Tonne, and Z. Chalabi, “Public health benefits of strategies to reduce greenhouse-gas emissions: household energy.,” *Lancet*, vol. 374, no. 9705, pp. 1917–29, Dec. 2009.

[10] J. A. Clarke, C. M. Johnstone, N. J. Kelly, P. A. Strachan, and P. Tuohy, “The role of built environment energy efficiency in a sustainable UK energy economy,” *Energy Policy*, vol. 36, no. 12, pp. 4605–4609, Dec. 2008.

[11] P. Torcellini, S. Pless, M. Deru, and D. Crawley, “Zero energy buildings: a critical look at the definition,” in *NREL/CP-550-39833*, 2006.

[12] I. Sartori, A. Napolitano, and K. Voss, “Net zero energy buildings: A consistent

definition framework," *Energy and Buildings*, vol. 48, pp. 220–232, May 2012.

[13] I. Sartori, A. Napolitano, A. J. Marszal, S. Pless, P. Torcellini, and K. Voss, "Criteria for definition of net zero energy buildings," in *International Conference on Solar Heating, Cooling and Buildings (EuroSun 2010)*, 2010.

[14] A. J. Marszal, P. Heiselberg, J. S. Bourrelle, E. Musall, K. Voss, I. Sartori, and A. Napolitano, "Zero Energy Building – A review of definitions and calculation methodologies," *Energy and Buildings*, vol. 43, no. 4, pp. 971–979, Apr. 2011.

[15] S. Pless and P. Torcellini, "Net-Zero Energy Buildings : A Classification System Based on Renewable Energy Supply Options," National Renewable Energy Laboratory, 2010.

[16] B. Griffith, N. Long, P. Torcellini, R. Judkoff, D. Crawley, and J. Ryan, "Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector," National Renewable Energy Laboratory, 2007.

[17] A. Belleri, F. Noris, U. . Oberegger, and R. Lollini, "Evaluation Tool For Net Zero Energy Buildings: Application On Office Building," in *Proceedings of the World Sustainable Energy Days, Wels, Austria 27*, 2013.

[18] F. Noris, A. Napolitano, and R. Lollini, "Measurement and Verification protocol for Net Zero Energy Buildings," IEA SHC/ECBCS Task 40/Annex 52 – Towards Net Zero Energy solar Buildings, 2013.

[19] A. . Marszal, J. . Bourrelle, E. Musall, P. Heiselberg, A. Gustavsen, and K. Voss, "Net Zero Energy Buildings-Calculation Methodologies versus National Building Codes," in *Proceedings of EuroSun (2010)*, 2010, vol. 2, no. May 2010.

[20] H. Rasekh, "Delivering the vision of sustainable buildings," University of Wollongong, 2013.

[21] Building Research Establishment Ltd, "Why BREEAM?," 2015. [Online]. Available: http://www.breeam.org/about.jsp?id=66. [Accessed: 04-Apr-2016].

[22] BRE Global Limited, "BREEAM: International," 2012. [Online]. Available: http://www.breeam.org/podpage.jsp?id=367. [Accessed: 29-Aug-2014].

[23] U.S. Green Building Council, "LEED Rating Systems," 2016. [Online].

Available: http://www.usgbc.org/leed#rating. [Accessed: 04-Apr-2016].

[24] New South Wales Office of Environment and Heritage, "How NABERS Works," 2014. [Online]. Available: http://www.nabers.gov.au/public/WebPages/ContentStandard.aspx?module=10&template=3&id=5&include=HowNabersWorks.htm&side=factsheets.htm. [Accessed: 01-Sep-2014].

[25] Green Building Council of Australia, "Introducing Green Star," 2013.

[26] Green Building Council of Australia, "The Value of Green Star - A Decade of Environmental Benefits," 2013.

[27] Y. Roderick, D. McEwan, C. Wheatley, and C. Alonso, "Comparison of energy performance assessment between LEED, BREEAM and Green Star," in *Eleventh International IBPSA Conference, Glasgow, Scotland, 27-30 July 2009*, 2009, pp. 1167–1176.

[28] B. K. Nguyen and H. Altan, "Comparative Review of Five Sustainable Rating Systems," in *2011 International Conference on Green Buildings and Sustainable Cities*, 2011, vol. 21, pp. 376–386.

[29] S. M. Bambrook, A. B. Sproul, and D. Jacob, "Design optimisation for a low energy home in Sydney," *Energy and Buildings*, vol. 43, no. 7, pp. 1702–1711, Jul. 2011.

[30] G. K. Oral, A. K. Yener, and N. T. Bayazit, "Building envelope design with the objective to ensure thermal, visual and acoustic comfort conditions," *Building and Environment*, vol. 39, no. 3, pp. 281–287, Mar. 2004.

[31] A. Syed, *Advanced building technologies for sustainability*, vol. 3. John Wiley & Sons, 2012.

[32] H. Sozer, "Improving energy efficiency through the design of the building envelope," *Building and Environment*, vol. 45, no. 12, pp. 2581–2593, Dec. 2010.

[33] R. Pacheco, J. Ordóñez, and G. Martínez, "Energy efficient design of building: A review," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 3559–3573, Aug. 2012.

[34] S. B. Sadineni, S. Madala, and R. F. Boehm, "Passive building energy savings: A

review of building envelope components," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 8, pp. 3617–3631, Oct. 2011.

[35] C. Franzetti, G. Fraisse, and G. Achard, "Influence of the coupling between daylight and artificial lighting on thermal loads in office buildings," *Energy and Buildings*, vol. 36, no. 2, pp. 117–126, Feb. 2004.

[36] M. Bodart and A. De Herde, "Global energy savings in offices buildings by the use of daylighting," *Energy and Buildings*, vol. 34, no. 5, pp. 421–429, Jun. 2002.

[37] M. Krarti, P. M. Erickson, and T. C. Hillman, "A simplified method to estimate energy savings of artificial lighting use from daylighting," *Building and Environment*, vol. 40, no. 6, pp. 747–754, Jun. 2005.

[38] M.-C. Dubois and Å. Blomsterberg, "Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review," *Energy and Buildings*, vol. 43, no. 10, pp. 2572–2582, Oct. 2011.

[39] P. Hoes, J. L. M. Hensen, M. G. L. C. Loomans, B. de Vries, and D. Bourgeois, "User behavior in whole building simulation," *Energy and Buildings*, vol. 41, no. 3, pp. 295–302, Mar. 2009.

[40] Z. Yu, B. C. M. Fung, F. Haghighat, H. Yoshino, and E. Morofsky, "A systematic procedure to study the influence of occupant behavior on building energy consumption," *Energy and Buildings*, vol. 43, no. 6, pp. 1409–1417, Jun. 2011.

[41] R. V. Andersen, J. Toftum, K. K. Andersen, and B. W. Olesen, "Survey of occupant behaviour and control of indoor environment in Danish dwellings," *Energy and Buildings*, vol. 41, no. 1, pp. 11–16, Jan. 2009.

[42] O. T. Masoso and L. J. Grobler, "The dark side of occupants' behaviour on building energy use," *Energy and Buildings*, vol. 42, no. 2, pp. 173–177, Feb. 2010.

[43] L. Klein, J. Kwak, G. Kavulya, F. Jazizadeh, B. Becerik-Gerber, P. Varakantham, and M. Tambe, "Coordinating occupant behavior for building energy and comfort management using multi-agent systems," *Automation in Construction*,

vol. 22, pp. 525–536, Mar. 2012.

[44] M. Boxwell, *Solar Electricity Handbook: A Simple, Practical Guide to Solar Energy: how to Design and Install Photovoltaic Solar Electric Systems*. Greenstream Publishing, 2012.

[45] P. Gevorkian, *Solar power in building design: the engineer's complete design resource*. McGraw-Hill, 2008.

[46] Volker Quaschning, "Technology Fundamentals: The Sun as an Energy Resouce," 2003. [Online]. Available: http://www.volker-quaschning.de/articles/fundamentals1/index_e.php. [Accessed: 18-Sep-2014].

[47] G. Stapleton, S. Neill, and G. Milne, "Photovoltaic systems | YourHome," 2013. [Online]. Available: http://www.yourhome.gov.au/energy/photovoltaic-systems. [Accessed: 18-Sep-2014].

[48] A. F. Sherwani and J. A. Usmani, "Life cycle assessment of solar PV based electricity generation systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 540–544, Jan. 2010.

[49] D. Simms, "Wind energy update," National Renewable Energy Laboratory, 2008.

[50] A. S. Bahaj, L. Myers, and P. A. B. James, "Urban energy generation: Influence of micro-wind turbine output on electricity consumption in buildings," *Energy and Buildings*, vol. 39, no. 2, pp. 154–165, Feb. 2007.

[51] P. Cooper, X. Liu, P. Kosasih, and R. Yan, "Modelling net zero energy options for a sustainable buildings research centre," in *12th Conference of International Building Performance Simulation Association, Building Simulation 2011 Conference*, 2011, pp. 2799–2806.

[52] A. D. Peacock, D. Jenkins, M. Ahadzi, A. Berry, and S. Turan, "Micro wind turbines in the UK domestic sector," *Energy and Buildings*, vol. 40, no. 7, pp. 1324–1333, Jan. 2008.

[53] N. Mithraratne, "Roof-top wind turbines for microgeneration in urban houses in New Zealand," *Energy and Buildings*, vol. 41, no. 10, pp. 1013–1018, Oct. 2009.

[54] K. Voss, I. Sartori, A. Napolitano, S. Geier, H. Gonzalves, M. Hall, P. Heiselberg, J. Widén, J. A. Candanedo, E. Musall, B. Karlsson, and P. Torcellini, "Load matching and grid interaction of net zero energy buildings," in *EUROSUN*

*2010 International Conference on Solar Heating, Cooling and Buildings*, 2010.

[55] J. Salom, A. J. Marszal, J. A. Candanedo, J. Widén, K. B. Lindberg, and I. Sartori, "Analysis of load match and grid interaction indicators in net zero energy buildings with high-resolution data," 2014.

[56] J. Salom, J. Widén, and J. Candanedo, "Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators," in *12th Conference of International Building Performance Simulation Association, Sydney, 14-16 November*, 2011, vol. 6, pp. 14–16.

[57] S. Deng, R. Z. Wang, and Y. J. Dai, "How to evaluate performance of net zero energy building – A literature research," *Energy*, vol. 71, pp. 1–16, Jun. 2014.

[58] A. J. Marszal, P. Heiselberg, R. Lund Jensen, and J. Nørgaard, "On-site or off-site renewable energy supply options? Life cycle cost analysis of a Net Zero Energy Building in Denmark," *Renewable Energy*, vol. 44, pp. 154–165, Aug. 2012.

[59] T. Ackermann, G. Andersson, and L. Söder, "Distributed generation: a definition," *Electric Power Systems Research*, vol. 57, no. 3, pp. 195–204, Apr. 2001.

[60] P. Järventausta, S. Repo, A. Rautiainen, and J. Partanen, "Smart grid power system control in distributed generation environment," *Annual Reviews in Control*, vol. 34, no. 2, pp. 277–286, Dec. 2010.

[61] R. H. Lasseter and P. Paigi, "Microgrid: a conceptual solution," *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, vol. 6. pp. 4285–4290 Vol.6, 2004.

[62] R. Lasseter, "Microgrids and distributed generation," *Journal of Energy Engineering*, pp. 144–149, 2007.

[63] A. Ipakchi and F. Albuyeh, "Grid of the future," *Power and Energy Magazine, IEEE*, vol. 7, no. 2. pp. 52–62, 2009.

[64] F. Katiraei and J. R. Aguero, "Solar PV Integration Challenges," *Power and Energy Magazine, IEEE*, vol. 9, no. 3. pp. 62–71, 2011.

[65] M. S. Al-Homoud, "Computer-aided building energy analysis techniques," *Building and Environment*, vol. 36, no. 4, pp. 421–433, May 2001.

[66] A. Foucquier, S. Robert, F. Suard, L. Stéphan, and A. Jay, “State of the art in building modelling and energy performances prediction: A review,” *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 272–288, Jul. 2013.

[67] H. Zhao and F. Magoulès, “A review on the prediction of building energy consumption,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 3586–3592, Aug. 2012.

[68] DOE2, “DOE2.com Home Page,” 2012. [Online]. Available: http://www.doe2.com/. [Accessed: 14-Oct-2014].

[69] D. B. Crawley, J. W. Hand, M. Kummert, and B. T. Griffith, “Contrasting the capabilities of building energy performance simulation programs,” *Building and Environment*, vol. 43, no. 4, pp. 661–673, Apr. 2008.

[70] NIBS, “Energy Analysis Tools | Whole Building Design Guide,” 2010. [Online]. Available: http://www.wbdg.org/resources/energyanalysis.php. [Accessed: 14-Oct-2014].

[71] D. B. Crawley, L. K. Lawrie, C. O. Pedersen, and F. C. Winkelmann, “Energy plus: energy simulation program,” *ASHRAE journal*, vol. 42, no. 4, pp. 49–56, 2000.

[72] D. B. Crawley, “Which weather data should you use for energy simulations of commercial buildings?,” *ASHRAE Transactions*, vol. 104, no. JUNE 1998, pp. 498–515, 1998.

[73] ASHRAE, “Measurement of Energy and Demand Savings,” 2002.

[74] T. Hoyt, K. H. Lee, H. Zhang, E. Arens, and T. Webster, “Energy savings from extended air temperature setpoints and reductions in room air mixing,” in *International Conference on Environmental Ergonomics 2009*, 2005, pp. 0–13.

[75] K. Gregory, B. Moghtaderi, H. Sugo, and A. Page, “Effect of thermal mass on the thermal performance of various Australian residential constructions systems,” *Energy and Buildings*, vol. 40, no. 4, pp. 459–465, Jan. 2008.

[76] Cox Architecture, “209150.00-A63-15.” 2011.

[77] Devon IT, “Green Computing |Thin Client Computing | Devon IT,” 2016. [Online]. Available: http://www.devonit.com/thin-client-education/green-computing. [Accessed: 04-May-2016].

[78] Jones Nicholson, “110020-M01.” 2011.

[79] Bates Smart, “S11081/1 - A21.02.” 2009.

[80] DesignBuilder Software Ltd, “DesignBuilder.” DesignBuilder, 2015.

[81] Australian Building Codes Board, “NCC Volume One - Energy Efficiency Provisions,” 2014.

[82] Graham Bell Bowman Architects, “836 CD 201.” 2012.

[83] Cox Architecture, “209150.00-A21-21/22,” 2011.

[84] Navigant Consulting, “2010 U.S. Lighting Market Characterization,” 2012.

[85] Standards Australia, “Interior lighting - General principles and recommendations, AS1680.1-1990.” Standards Australia, 1990.

[86] Bureau of Resources and Energy Economics, “2014 Australian Energy Update,” 2014.

[87] Standards Australia, “Electromagnetic compatibility (EMC) Part 3.2: Limits—Limits for harmonic current emissions (equipment input current ≤16 A per phase) AS61000.3.2-2013,” vol. 2, no. 2009. Standards Australia, 2013.