Investigation of Energy Efficient approaches for the energy performance improvement of commercial buildings

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ETTV, Energy efficiency, Energy-Efficient, Energy performance, Living wall, Green facade, Green roof, Commercial building, Temperature, Cooling energy, Quantification
Abstract

Energy efficiency of buildings is attracting significant attention from the research community as the world is moving towards sustainable buildings design. Energy efficient approaches are measures or ways to improve the energy performance and energy efficiency of buildings. This study surveyed various energy-efficient approaches for commercial building and identifies Envelope Thermal Transfer Value (ETTV) and Green applications (Living wall, Green facade and Green roof) as most important and effective methods. An in-depth investigation was carried out on these energy-efficient approaches. It has been found that no ETTV model has been developed for sub-tropical climate of Australia. Moreover, existing ETTV equations developed for other countries do not take roof heat gain into consideration. Furthermore, the relationship of ETTV and different Green applications have not been investigated extensively in any literature, and the energy performance of commercial buildings in the presence of Living wall, Green facade and Green roof has not been investigated in the sub-tropical climate of Australia. The study has been conducted in two phases. First, the study develops the new formulation, coefficient and benchmark value of ETTV in the presence of external shading devices. In the new formulation, roof heat gain has been included in the integrated heat gain model made of ETTV. In the 2nd stage, the study presents the relationship of thermal and energy performance of (a) Living wall and ETTV (b) Green facade and ETTV (c) Combination of Living wall, Green facade and ETTV (d) Combination of Living wall, Green Roof and ETTV in new formulations. Finally, the study demonstrates the amount of energy that can be saved annually from different combinations of Green applications, i.e., Living wall, Green facade; combination of Living wall and Green facade; combination of Living wall and Green roof. The estimations are supported by experimental values obtained from extensive experiments of Living walls and Green roofs.
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<tr>
<td>ETTV</td>
<td>Envelope Thermal Transfer Value</td>
</tr>
<tr>
<td>OTTV</td>
<td>Overall Thermal Transfer Value</td>
</tr>
<tr>
<td>RTTV</td>
<td>Roof Thermal Transfer Value</td>
</tr>
<tr>
<td>RIRDC</td>
<td>Rural Industries Research and Development Corporation</td>
</tr>
<tr>
<td>ASRDH</td>
<td>Australian Solar Radiation Data Handbook</td>
</tr>
<tr>
<td>AIRAH</td>
<td>Australian Institute of Refrigeration and Heating</td>
</tr>
<tr>
<td>BOM</td>
<td>Bureau of Meteorology of Australia</td>
</tr>
<tr>
<td>BRAIN</td>
<td>Brisbane Rainforest and Information Network</td>
</tr>
<tr>
<td>COAG</td>
<td>Council of Australian Government</td>
</tr>
<tr>
<td>NABERS</td>
<td>National Built Environment Rating System</td>
</tr>
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### Nomenclature

- **a**: operating hours of a day for air-conditioning
- **A<sub>t</sub>**: total building envelope area (m<sup>2</sup>)
- **A<sub>te</sub>**: total area of envelope and roof (m<sup>2</sup>)
- **A<sub>s</sub>**: area of south facing wall (m<sup>2</sup>)
- **A<sub>e</sub>**: area of east facing wall (m<sup>2</sup>)
- **A<sub>n</sub>**: area of north facing wall (m<sup>2</sup>)
- **A<sub>w</sub>**: area of west facing wall (m<sup>2</sup>)
- **b**: operating days in a week for air-conditioning
- **B**: atmospheric extinction coefficient
- **C<sub>m</sub>**: multiplication of operating hours of building in day and in a week
- **C**: ratio of diffuse radiation on a horizontal surface to direct normal irradiation
- **CF**: solar correction factor for fenestration
- **COP**: coefficient of performance of Chiller at design point
- **C<sub>pa</sub>**: Specific heat of air = 1.006 KJ/KgK
- **C<sub>H</sub>**: Non dimensional bulk heat transfer coefficient = 0.002 to 0.02 for smooth to rough surface
- **C<sub>wwr</sub>**: equivalent to 1-WWR
- **D**: number of cooling degree days
- **E<sub>c</sub>**: annual cooling energy consumption (MWh/yr) or (KWh/yr)
E_{cw} \quad \text{annual cooling energy consumption in presence of living wall system on west facing wall (MWh/yr) or (KWh/yr)}

E_{cf1} \quad \text{annual cooling energy consumption when Green facade system is in front of west facing wall (MWh/yr) or (KWh/yr)}

E_{cf2} \quad \text{annual cooling energy consumption when Green facade system is in front of window (MWh/yr) or (KWh/yr)}

E_{cb} \quad \text{annual cooling energy consumption when both system is present (MWh/yr)}

E_{sc} \quad \text{effective shading coefficient of external shading devices (in this case plant)}

G_{nd} \quad \text{normal direct irradiation respectively, } G_{nd} = A*C_n/(e^{B/\sin\beta}) (W/m^2), \text{ where } C_n \text{ is clearness number}

ETTV_{gf1} \quad \text{heat gain in terms of ETTV due to Green facade system on west facing wall (W/m^2)}

ETTV_{gf2} \quad \text{heat gain in terms of ETTV due to Green facade system on west facing window (W/m^2)}

ETTV_b \quad \text{weighted average heat gain in terms of ETTV of building due to living wall system on west wall (W/m^2)}

ETTV_{b1} \quad \text{weighted average heat gain in terms of ETTV of building due to Green facade system on west wall (W/m^2)}

ETTV_{b2} \quad \text{weighted average heat gain in terms of ETTV of building due to Green facade system on west facing fenestration (W/m^2)}

ETTV_{bo} \quad \text{weighted average heat gain in terms of ETTV of building due to presence of both system in west facing wall (W/m^2)}

ETTV_n \quad \text{ETTV of north facing of wall (W/m^2)}

ETTV_s \quad \text{ETTV of south facing wall (W/m^2)}

ETTV_e \quad \text{ETTV of east facing wall (W/m^2)}

ETTV_{lg} \quad \text{ETTV of living wall system on west wall and Green facade system on west facing window (W/m^2)}

ETTV_{lw} \quad \text{ETTV of west facing wall due to living wall system (W/m^2)}

ETTV_{t} \quad \text{total heat gain of building (W/m^2)}

G \quad \text{average radiation on a roof surface (W/m^2) } = \frac{H}{\Delta t}, \text{ H is daily horizontal surface irradiation, } \Delta t \text{ is time length (24 x 3600) sec}

H_g \quad \text{total heat gain of the building including wall, roof and internal gain (W/m^2)}

h \quad \text{heat transfer coefficient for air (50-100 W/m^2K)}

h_o \quad \text{outside total heat transfer coefficient between roof and ambient (W/m^2K)}
h_c  convection heat transfer coefficient (W/m²K), h_c = \rho_aC_{pa}C_{hu}

h_0g  outside total heat transfer coefficient between Green roof and ambient air, h_0g (W/m²K)

h_g  radiative heat transfer coefficient between Green roof surface and sky, h_g (W/m²K)

HW  hot water reheat system usually written as HW

I_0  solar intensity behind canopy (W/m²)

I_1  average total irradiance on vertical surface (W/m²)

K  light extinction coefficient

LAI  leaf area index of plant

n  correction factor in the part load performance of Chiller

Q_{int}  internal heat gain due to occupants, lighting and equipment (W/m²)

R_{so}  surface film resistance equivalent to 0.044 (m²K/W)

R_c  thermal resistance of concrete wall or roof (m²K/W)

R_l  thermal resistance of living wall (m²K/W)

SC  shading coefficient of fenestration

SF  solar factor (W/m²)

T_a, T_\alpha  Ambient temperature, 25-40 °C

T_i  design indoor air temperature 21, 0°C

T_c  concrete roof surface temperature, 0°C

T_{ai}  design indoor air temperature 21°C,

T_{ao}  monthly mean outdoor temperature (0°C)

T_l  air gap temperature due to living wall system (°C)

T_g  temperature of the Green roof surface (°C) measured from the set up

T_{sго}  surface temperature of living wall (°C)

T_{sgi}  sub-Surface temperature of living wall (°C)

T_{so}  outside surface temperature of steel wall (°C)

T_{si}  internal surface temperature of steel wall (°C)

T_{sco}  outside surface temperature of concrete wall (°C)

T_{sci}  internal surface temperature of concrete wall (°C)

T_r  indoor air temperature of Green shed (°C)

T_{sky}  sky temperature typically 2-20 K below ambient temperature So, T_{sky} = T_a-10 K or T_{sky} = T_a-20 K

T_{sri}  internal surface temperature of steel roof under Green roof (°C)

T_{sri}  internal surface temperature of steel roof under Green roof (°C)
TD_{eq}, equivalent temperature difference (°C) for opaque wall
TD_{eqg} equivalent temperature difference (°C) for opaque wall in presence of living wall
T_{sc} total shading coefficient due to window glass and deciduous plants infront of window
ΔT temperature difference between outdoor and indoor condition for window (°C)
Δt design indoor-outdoor temperature difference (°K)
U_{wi} thermal conductivity value of wall (W/m²K)
U_{wa} thermal transmittance of wall (W/m²K)
U_{f} thermal transmittance of fenestration (W/m²K)
U_{l} U value of living wall (W/m²K)
U_{a} thermal transmittance of air gap (W/m²K)
U_{g} U value of Green roof
U_{r} thermal conductivity value of roof (W/m²K)
Γ_{t} total heat transfer coefficient of Green roof (U_{g}) and concrete roof (U_{c})
VAV Variable area volume
WWR window to wall ratio
α absorption coefficient of wall due to solar radiation
γ linear function or correlation fuction for design space cooling load
ρ_{a} density of air = 1.28 kg/m³ = P/RT_{a}, Atmospheric pressure 100 KPa, R= 287 J/kgK
v velocity of wind 2.8 m/sec
σ stefan-Boltzmann constant (5.67 x 10^{-8} W m²K^{-4})
ε surface emissivity for long wave thermal radiation varies from (0.9 to 0.95)

*Note: Some of the temperature calculated as 0 K during calculation to adjust the calculation process if the unit of U value is in W/m²K. However, the measured temperature during experimental investigation was in °C.
Glossary

**Smart glass**: Smart glass is made of tinted glass and special type of plastic. These are sandwiched together

**Biodiversity**: It is the degree of variation of life forms within a given species, ecosystem biome and an entire planet

**Passive cooling**: The type of cooling that can be obtained from natural sources or other Green applications on building wall and roof
Statement of Original Authorship

The work contained in this thesis has not been submitted previously to meet requirement of an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference has been made.

QUT Verified Signature

Signature

Date 21 March 2013
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List of Publications

Conference paper

1. Investigation of cooling energy performance of commercial building in sub-tropical climate through the application of Living wall and Green roof (Published in proceedings of Healthy Building, 10th International Conference, International Society of Indoor Air Quality and Climate (ISIAQC), Brisbane, Australia, 8-12 July, 2012)

2. Estimation of energy saving of commercial building by Living wall and Green facade in sub-tropical climate of Australia (Published in proceedings of 7th International Green Energy Conference, IGEC, Dalian, China, 28-30 May, 2012)

Journal

1. Investigation of Envelope Thermal Transfer Value (ETTV) in Sub-tropical climate of Australia (Submitted in Energy and Buildings)

2. Energy performance of commercial building by Living wall and Green facade in sub-tropical climate of Australia (In preparation for Journal of Renewable and Sustainable Energy)

3. Thermal Performance of Living wall and Green Roof for energy performance of commercial building in sub-tropical climate of Australia (In preparation for Energy and Buildings)
Chapter 1: Introduction

1.1 The global scenario of energy consumption of buildings

Energy efficiency of buildings has recently become a major issue because of growing concerns of CO\textsubscript{2} and other greenhouse gas emissions, and scarcity of fossil fuels. Buildings worldwide account for a surprisingly high 40% of global energy consumption (Krarti, 2012; Krarti, 2011; Bribian et al., 2009). If the energy consumed in manufacturing steel, cement, aluminium and glass used in construction of buildings is being considered, this consumption would be more than 50% (Energy Efficiency in Buildings, 2009). Energy efficiency of buildings plays a vital role in designing a new building, assessing its energy consumption as per design, and application of energy efficient technologies during construction and operation of the building. As buildings consume about half of global energy consumption, energy efficiency of buildings is critically important in addressing climate change. In Australia, the energy used by buildings accounts for approximately 20% of Australia's greenhouse gas emissions, this is split fairly evenly between homes and commercial buildings (Buildings, 2010). This research will address some of the approaches to improve energy efficiency of buildings.

The next section of this chapter will discuss energy-efficient approaches, and how they relate to energy efficiency improvement. Later on, energy-efficient approaches and their relationship to present research have been discussed in brief.

1.2 Energy-efficient approaches and energy efficiency of buildings

Energy-efficient approaches are the measures that aim to improve the energy efficiency of buildings. These measures are the ways through which the energy consumption of a building can be reduced while maintaining or improving the level of comfort in the building. Therefore, an energy-efficient approach for buildings can be defined as an approach that can assist in reducing energy consumption in the form of electricity, improving the greenhouse gas (GHG) impact of operations and reducing operating costs of buildings.
The energy efficiency of a building is the extent to which the energy consumption per square metre of floor area or per square metre of envelope area (KWh/m² yr) can be reduced compared to benchmarks for that particular type of building under defined climatic conditions. The benchmarks are derived by analysing data on different building types within a given country. The typical benchmark is the median level performance of all buildings in a given category and good practice presents the top quartile performance. Comparisons with simple benchmarks of annual energy use per floor or envelope area allow the determination of the energy efficiency level of the building and therefore, priority areas for action can be identified. Benchmarks are applied mainly to heating, cooling and air-conditioning. These benchmarks vary from country to country and depend on the agreement of corresponding countries’ building code boards and experts in that area.

An efficient building is one that applies energy-efficient technologies while operating as per design, supplies the amenities and features appropriate for that kind of building, and which can be operated in such a manner as to have a low energy use compared to other similar buildings (Olofsson et al., 2004; Meier et al., 2002). The concept of “energy-efficient buildings” has some implications that depend on regulations, economics, energy demand and the environment. There are many concepts regarding energy-efficient buildings; the elements can be divided into three parts (Olofsson et al., 2004; Meier et al., 2002).

(a) The building must contain energy-efficient technologies, when operating as designed, to effectively reduce energy use.

(b) The building must deliver the amenities and features appropriate for that kind of building.

(c) The building must be operated in an efficient manner. The evidence of this operation is low energy use relative to other similar buildings.
1.3 Building energy efficiency, energy-efficient approaches and present research

Energy consumption by air-conditioning of commercial buildings is one of the key elements that should be reduced to improve the energy efficiency of buildings. In this case, the thermal performance of the exterior building envelope is responsible for a large portion of total cooling energy consumption of the building. Climatic conditions can enhance the cooling energy consumption by up to 77% (Ibraheem, 2007). In Australia, air-conditioning constitutes 21% of total building energy consumption of commercial buildings as shown in Figure 1.1 (CIE, 2007).

![Figure 1.1: Energy consumption by different subsectors](image_url)

Improvement of cooling energy consumption leads to less energy consumption by air-conditioning, which leads to improvement in energy efficiency of buildings. Present research will address the improvement in energy efficiency by applying the concept of Envelope Thermal Transfer Value (ETTV) and application of Living wall, Green facade and Green roof technologies to the building envelope design. ETTV can be considered as the energy benchmarking index that leads to the annual cooling energy requirement per envelope area (KWh/m² yr) of the building. An appropriate energy performance index for the building envelope and the application of Living wall and Green roof can lead to significant energy
saving in commercial buildings. Krarti (2012) proposed the improvement of building envelope efficiency as one of the energy conservation measures through which the energy consumption of the building can be reduced. Olofsson et al. (2004) and Meier et al. (2002) suggested that efficiency of the building can be evaluated in terms of the calculated heat loss or heat gain through the envelope. In the present research, one of the main focuses is to consider heat gain and heat loss from energy through building envelopes. The Envelope Thermal Transfer Value (ETTV) of a new building can be considered as the energy benchmark index to determine the envelope performance of the building in terms of heat gain at the design stage. Chua and Chou (2010a) established ETTV as an energy-efficient approach to improve the performance of commercial buildings. As ETTV is used to estimate the cooling energy requirements of buildings, it can easily evaluate the capacity of chillers required for the design purpose, which eventually reduces the chance of using oversized or overcapacity chillers. Living wall, Green facade and Green roof are energy-efficient, passive cooling technologies that can reduce the energy consumption of the building. Thus, consideration of appropriate energy-efficient approaches in the design stage and application of them in the operation stage, based on envelope characteristics and energy consumption requirements, is the key to improve the energy efficiency of buildings.

Alam and Theos (2008) identified two stages of energy efficiency improvement and proposed to investigate alternative elements that can be used in buildings during the construction stage to improve the energy performance. During this construction phase, selection of different elements like internal walls, external walls, foundations and the roof have significant implications in energy consumption. The elements that are responsible for energy consumption in the operation phase of the building are: space heating equipment, space cooling equipment, lighting equipment, refrigeration and chilling units, ventilation, water heating, electronics, computers and, cooking appliances. However, it is better to examine energy efficiency at the design stage of the building so that predicted energy performance of the buildings can be analysed and necessary measures to improve the energy efficiency can be taken. It has been found that the most important decisions regarding building sustainability can be made in the early design stages by the architects or building designers (Dahl et al., 2005; Lam et al., 2004). Envelope Thermal Transfer Value (ETTV), Living wall and Green roof can be used as energy-efficient approaches for the design and operation stage of buildings. A standard ETTV determined for a region or country can be used as a benchmark value for a specific climate zone in order to design an energy-efficient building. ETTV
enhances the scope to design an energy-efficient envelope that assists in obtaining energy efficiency of a building (Devgan et al., 2010). At the same time, Living wall and Green roof applications can be considered during the design stage to further improve the energy performance of the building.

The ETTV approach can also be applied for an existing building to evaluate its performance with the benchmark ETTV standard and reduction of its value through improvement in potential areas. Among the potential areas, wall and roof areas can be identified to implement Living wall, Green facade and Green roof technologies for further reduction of ETTV and cooling energy requirements of the building. The process of applying ETTV, Living wall, Green facade and Green roof in design and operation stage of the building is shown in Figure 1.2.

![Diagram of ETTV process]

**Figure 1.2: Process of applying ETTV, Living wall, Green facade and Green Roof**

The next section will highlight the research problems, research questions and solutions explored to address the research questions.
1.4 Research problems and research questions

1.4.1 Research Problems

Based on extensive literature review reported in the next chapter (Chapter 2), the main research problems can be summarised as follows:

(a) Formulation of ETTV with external shading devices for different building orientations and determination of coefficients of Envelope Thermal Transfer value equation.

(b) Estimation of heat gain and cooling energy by inclusion of the roof effect in an integrated heat gain model.

(c) Establishing the relationship between Living wall and Green façade with ETTV.

(d) Experimental investigation of thermal and energy performance of different combinations of Green applications, i.e. Living wall only, Green facade only, Living wall and Green facade combination, Living wall and Green roof combination and estimation of energy saving if these are applied to real building application.

1.4.2 Research Questions

Relevant research questions can be written as follows:

(a) What would be the ETTV formulations for Australia and what would be the relationship between ETTV and Living wall, Green façade, combination of Living wall and Green facade, combination of Living wall and Green roof in the new ETTV formulation?

(b) What would be the new formulation, coefficient and benchmark value of ETTV in the presence of external shading devices?

(c) What would be the effect of inclusion of heat gain through roof in an integrated heat gain model?
(d) How much energy can be saved annually from different combinations of Green applications, like Living wall, Green façade, combination of Living wall and Green facade, and combination of Living wall and Green roof.

1.5 Solutions explored to address the research questions

To develop the new formulation, coefficient and benchmark value of ETTV of commercial buildings in Australia, detailed data of some real commercial buildings located in the subtropical climate zone of Australia have been studied. Thermal simulation of similar model buildings has been performed to retrieve hourly heat gain using different construction materials. ETTV formulation has been developed from analysis of a huge number of data sets. Roof heat gain has been included in the ETTV formulation. An ETTV benchmark value has been determined, which can be used for energy efficiency improvement in commercial buildings. Developed ETTV formulations have been used for energy efficiency improvement of commercial building using energy-efficient approaches (Living wall, Green facade and Green roof). Experimental investigation of Green applications has been conducted in a real experimental setup. The annual cooling energy saving with different Green applications individually and in combination has been demonstrated.

1.6 Practical Importance of the study

1.6.1 Envelope Thermal Transfer Value (ETTV)

Envelope Thermal Transfer Value, ETTV (W/m^2) is a method of determining average heat gain of a building through its envelope considering all heat gain components of that building. It is a parameter that measures the energy efficiency of the building without inhibiting the design options and creativity of the architects. The factors that affect ETTV are orientation, wall materials, roof materials, envelope colour, glass type, external shading on windows or wall, latitude, solar radiation etc. For a given location or latitude, it is assumed that the climatic factors and the local parameters such as acclimatisation levels may not vary, but the
interaction of the architectural parameters such as orientation of the building, type of glazing on the windows, shading devices etc. may vary. Therefore it is very important to investigate heat gain parameters to determine the coefficients, formulation and ETTV value for energy performance investigation as ETTV has a relationship with building energy consumption.

The advantages of ETTV have been demonstrated by many researchers (Chua and Chou, 2010a; Chua and Chou, 2011; Devgan et al., 2010; Vijayalaxmi, 2010;). ETTV is a benchmark design value of buildings that has been used by different countries and the advantages are many. The ETTV can be used to control building energy use at the design stage, to predict the future energy demand of the building, to implement as energy-efficient building design protocols and to practice as an energy management benchmark value. ETTV encourages experts and researchers to suggest ways to improve energy efficiency in building, to encourage climate-responsive building planning and design. Furthermore, ETTV is one of the simplest methods and adoption of it helps experts, designers, engineers and architects to design buildings for lower ETTV and hence lower energy consumption. Due to the above advantages, the study of ETTV has practical importance in improving the energy performance of buildings.

1.6.2 Living wall, Green facade and Green roof technologies

Living wall and Green roof are emerging technologies that have been used in different countries to improve the thermal performance of buildings through its application on walls and roofs respectively. These systems are made up of suitable plants for specific climates, planted or potted in soil having several layers and then affixed in a structure. Living walls are sometimes called Green walls or Vertical vegetation. The Living wall system can be grown directly onto a building’s façade, or it can be grown on a separate structural system that is adjacent to the wall and sometimes attached to it. Living walls are designed, built and maintained vegetation elements associated with a building. Green facade systems can be installed by wire or a pot system in front of a building’s walls or windows. Green roof systems are now being introduced in many buildings around the world to provide greater thermal performance and roof insulation. A Green roof is a surface that is partially or completely covered with vegetation and growing medium over a waterproofing membrane. A
Green roof acts as an insulation barrier and it reduces the amount of solar energy absorbed by the roof membrane, thus leading to cooler temperatures beneath the surface.

Living wall, Green facade and Green roofs are passive cooling techniques used in envelope and roof design and have been discussed in some studies (Castleton et al., 2010; Okba, 2005; Kontoleon and Eumorfopoulou, 2010). Passive cooling techniques are the design attempts to integrate principles of physics into the building exterior envelope to slow down heat transfer into a building. This includes heat conduction, convective heat transfer, and thermal radiation primarily from the sun. As ETTV deals with building envelope and heat gain by envelope, so it can be correlated with passive cooling techniques i.e. Living walls and Green roofs that can reduce or eliminate the effect of conduction heat gain and thermal radiation on buildings. To eliminate thermal radiation, shading is one of the options of passive cooling techniques. Shading a building from solar radiation can be achieved in many ways. Buildings can be orientated to take advantage of winter sun i.e. longer in the east or west dimension, while shading walls and windows from direct hot summer sun. Methods of shading against low eastern and western sun are deciduous plantings. Climbing plants can be fitted to existing buildings to reduce solar heat gain. Therefore, the selection of appropriate orientations for Living wall and Green facade application to reduce ETTV and cooling energy consumption therefore, improves thermal and energy performance. These require further investigation in the presence of these systems for specific climatic conditions. The cooling energy saving potential, due to use of these passive cooling techniques, encourages researchers to investigate the quantification of thermal and energy performance of these applications on real buildings.

The advantages of using Living wall, Green facade and Green roof are many. The benefits of using these Green applications have been reported by many researchers, academics and scientists (Hopkins and Goodwin, 2011; Carpenter, 2008; Yang et al., 2008; GRHCl, 2008; Theodosiou, 2009; ESAG, 2004; Almusaed, 2011; Wong et al., 2010a; Wong et al., 2010b; Wong et al., 2003; Onmura et al., 2001, Carter et al., 2008; Dunnett et al., 2007; Spolek, 2008). Using these Green applications, economic, environmental, and social benefits can be obtained (The City of Bloomington, USA, 2010). Use of Living wall, Green facade and Green roof at the design and operation stage of the building can reduce the ETTV, energy consumption, GHG emissions, urban heat island effect, energy costs and noise pollution. These approaches improve the thermal and energy performance of buildings in a specific
climate, as well as indoor air quality, and encourage the practice of using Green and clean energy. In Australia, the amount of energy saving that can be achieved by using these applications for a specific climate have not been studied extensively.

1.7 Methodology

This research has been undertaken in two stages. At the first stage, the data relevant to commercial building heat gain parameters, air-conditioning, building drawing and plan view have been collected from different reliable sources (consultancy firms, AIRAH handbook, ASRDH handbook and literatures). The simulation of data has been conducted and hourly heat gain has been retrieved from simulation. Using mathematical modelling and linear regression, the coefficients of ETTV have been determined. The external shading coefficient due to an overhang condition located at the top of windows has been determined using mathematical model and solar radiation data. The new ETTV formulation has been developed and ETTV value has been determined. A comparative study has been conducted between simulated cooling energy by software and ETTV based estimation. A relationship has been established between ETTV and space cooling energy consumption for validation of ETTV coefficients and determination of energy management benchmark value. Roof heat gain has been included in an integrated building heat gain model for accurate estimation of cooling energy consumption.

At the second stage, the mathematical formulation for quantification of heat gain and energy performance of a commercial building in the presence of Living wall, Green facade and Green roof have been developed using the ETTV equations developed in the first stage for envelope and steady state heat gain of roofs in the sub-tropical climate of Australia. Then experimental investigation has been conducted for Living wall and Green roof, using a setup made of Australian native plants. For the Green facade application, the external shading coefficient has been determined using mathematical modelling solar radiation data and leaf area index of plants. Thermal performance of various points including internal air, ambient and air gap has been investigated. Then, the predicted thermal performance of the building wall and roof has been investigated. Using all of the temperature data, external shading coefficient and mathematical modelling, the quantification of heat gain and energy
performance of a commercial building in the presence of different combinations of Green applications has been investigated and annual energy saving has been determined.

### 1.8 Thesis Outline

The thesis focuses on investigation of energy efficient approaches i.e. ETTV and Green applications (Living wall, Green façade and Green roof) for the energy performance improvement of commercial buildings. The determination of ETTV formulations, ETTV value, its coefficients and ETTV-based cooling load estimation including the external shading coefficient is one focus of the thesis. The inclusion of roof heat gain with ETTV for mid-rise commercial buildings in a building-integrated heat-gain model is another focus of the study. Another key focus of the thesis is to establish the relationship between Green applications and ETTV. This thesis determines the amount of annual cooling energy saving i.e. energy performance improvement of commercial buildings using different combinations of Green applications with ETTV. Figure 1.3 shows the organisation of the thesis. This thesis consists of six chapters. Chapter 1 discusses the global energy consumption scenario, energy efficient approaches, research problems, research questions, practical importance of the study and methodology followed. Chapter 2 presents an extensive literature review regarding the ETTV, Living wall, Green facade and Green roof technologies, and finally the research gap. Chapter 3 presents the methodology adopted to perform the research study. Chapter 4 presents details of ETTV coefficients, ETTV value, formulation, relationship with cooling energy, ETTV-based estimation, roof heat gain effect, case studies and finally, results and discussion. Chapter 5 illustrates and contributes the mathematical modelling of heat gain and energy estimation in presence of Living wall, Green facade and Green roof using ETTV. Chapter 5 also demonstrates the experimental investigation of Living wall and Green roof, the mathematical investigation of Green facade, details of the data measuring points, thermal performance of Green and Control shed, predicted thermal performance in real building application. Finally the results of the energy performance of different combinations of Living wall, Green facade and Green roof have been shown in chapter 5. Chapter 6 discusses and outlines the key findings, contributions, limitations, suggestions and finally, conclusions.
Figure 1.3: A brief overview of investigation of energy-efficient approaches in thesis
Chapter 2: Literature Review

Summary

According to the International Energy Agency (IEA), energy efficiency improvement in buildings is one of the methods that could reduce the world’s energy needs in 2050 by one third, and help control global emissions of greenhouse gases (IEA report, 2006). To improve the energy efficiency of the buildings, there are many methods which have been studied by researchers around the world. All the methods have some advantages and many scholarly articles have been published on these methods. A brief description of different methods and their respective advantages to improve the energy efficiency of buildings have been discussed first in this chapter. A comparative study has then been conducted amongst all the methods to identify which have more benefits compared to others. Amongst all the methods, the improvement of building envelope performance using ETTV, application of Living wall, Green facade and Green roof have been selected in this study due to their huge advantages on the energy efficiency improvement of buildings. A comprehensive literature review on Envelope Thermal Transfer Value (ETTV) studied in different countries has been demonstrated. Present methods of energy efficiency improvement in Australia are also presented. Living wall, Green facade and Green roof technologies including plant selection and their suitability, and their thermal and energy performance have been extensively discussed. Finally, the research gaps in improving the energy performance of commercial buildings in the sub-tropical climate of Australia have been discussed.

The structure of this chapter and the flow of contents are presented in Figure 2.1.

2.1 Introduction

An extensive amount of literature has been studied during the course of this research and has been discussed in this chapter. Literature review is divided into several sections and each section leads to a subsequent section and therefore, maintains a flow of content. Section 2.2 describes different energy-efficient approaches found in the literature. The benefits of using ETTV and Green applications are demonstrated in sections 2.3 and 2.4. A comparative study of different systems is shown in section 2.5 and it has been demonstrated that use of Green applications and the ETTV approach provide more benefits compared to other methods. Section 2.6 outlines an extensive literature review regarding the ETTV studied in different countries. Energy efficiency programs, the present approach of energy consumption analysis in Australia, and comparison of these with the ETTV approach are outlined clearly in section 2.7. Section 2.8 illustrates plant suitability and thermal and energy performance of Green
applications examined in different countries. A comparative study regarding the Green applications, combination of different Green applications and relationship to ETTV adoption studied in different countries is demonstrated in section 2.9. Green applications in Australia are discussed in section 2.10. Based on the extensive literatures reviewed in sections 2.2-2.10, the research gap is presented in section 2.11.

The next section will discuss the energy efficiency improvement of buildings and different ways to improve the energy efficiency of the buildings.
2.2 Building energy efficiency improvement

There are many approaches to improve the energy efficiency of buildings. Usually the designer and architects use different tools to make a building energy-efficient at the design stage. Measures and techniques may be different for existing buildings. It varies as per nature of building systems and the age of a building itself. Some of the areas are identified by some researchers to improve the energy efficiency of buildings. These include improving the performance of building envelope system, efficient HVAC system, application of Green technologies and others (Krarti, 2012; Krarti, 2011; Sozer, 2010; Markis and Paravantis, 2007; Buildings Energy Efficiency, 1992). Some of the approaches are discussed in the next sections.

2.2.1 Improvement of HVAC system

Most HVAC systems are designed for temperature control without any concern regarding energy efficiency. More than 60% of the energy delivered to the buildings in hot and humid climatic regions is consumed by the HVAC system (Al-Azhari et al., 2002). Shekhar and Chung (1998) used a simulation to evaluate the five most commonly used HVAC systems in commercial buildings, based on their thermal and energy performance. There are some techniques that can be followed and energy can be conserved in a HVAC system during operation, these techniques are recommended by many researchers, engineers and academics (Krarti, 2012; Krarti, 2011). These include operation of HVAC systems: Operating the HVAC system only when it is required, for example there is no need to provide ventilation during unoccupied periods; this strategy can be followed by building operators and occupants. Eliminating overcooling and overheating of the conditioned space to improve comfort levels and avoid energy waste is another option.

2.2.2 Improvement in lighting system

Lighting is a critical component of energy use in large office buildings. Hawken et al. (2000) reported that homes and offices consume 20% - 30% of total energy consumption. Krarti (2012) proposed a simple equation to calculate the total energy used by lighting system. This
equation can be used to calculate the energy saving due to any retrofit measure for the lighting systems. The energy consumption due to lighting needs to be calculated before and after the retrofit. The difference between the two estimated energy uses represents the energy savings. Krarti (2012) proposed the following lighting equation

$$K_{\text{h,light}} = \sum N_{\text{lum,j}} \cdot W_{\text{R, lum,j}} \cdot N_{\text{h,j}}$$  \hspace{1cm} (2.1)

Where,

- $N_{\text{lum,j}}$ is the number of lighting luminaries i.e. set of ballast, electrical wiring, housing and lamps of type j in the building to retrofitted.
- $W_{\text{R, lum,j}}$ is the wattage rating of both lamps and ballast for each luminary of type j
- $N_{\text{h,j}}$ is the number of hours per year when the luminaries of type j are operating
- J is the number of luminary types in the building.

To improve the energy efficiency of the lighting system, it is necessary to use reduced wattage rating of luminaries. Reduction of uses of luminaries and reduction of number of luminaries are other options to improve efficiency. However, human comfort, occupants, speed and accuracy requirements and background contrast are some factors that need to be considered as well. Energy-efficient lighting systems, for example high efficiency fluorescent lamps and compact fluorescent lamps, can improve the energy efficiency of a lighting system.

Another technique of improving energy efficiency of lighting systems is use of occupancy sensors. Occupancy sensors save energy by automatically turning off the lights in spaces that are not occupied. Infrared sensors and ultrasound sensors are available now and they can be used in different occupant conditions. Love (1998) estimated that 30% energy savings can be achieved if time delays on occupancy control systems are taken into account.

### 2.2.3 Thermal Energy Storage System

Thermal energy storage systems (TES) are defined as the short-term storage of energy for later use when heating and cooling is needed. TES is based on two major principles. Firstly, sensible energy storage by increasing (for heating applications) or decreasing (for cooling
applications) the temperature of the storage medium (water, for instance). Secondly, latent energy storage by changing the phase of the storage medium-phase change materials (PCM). Recently much research is now ongoing regarding the use of PCMs in conventional building materials to enhance the energy storage capacity through latent heat of the PCM. The building material concept currently being studied uses a PCM added to gypsum wallboard, a material in widespread use in both residential and commercial buildings. The primary application is passive solar heating of a building, where the PCM wallboard would allow solar energy to supply a larger fraction of building heating. Amar and Farid (2004) used the thermal energy system concept and reported that energy storage in the walls, ceiling and floor of buildings may be enhanced by encapsulating suitable phase change materials (PCMs) within these surfaces. This captures solar energy directly and increases human comfort by decreasing the frequency of internal air temperature swings and maintaining the temperature closer to the desired temperature for a longer period of time.

2.2.4 Improvement in designing of building envelope

A building’s location and surroundings play a key role in regulating its temperature and heat gain. For example, trees, landscaping, and hills can provide shade and block wind. In cooler climates, designing buildings with south-facing windows increases the amount of sun entering the building, minimizing energy use by maximizing passive solar heating. Tight building design, including energy efficient windows, well-sealed doors, and additional thermal insulation of walls, basement slabs, and foundations can reduce heat loss by 25 to 50% (Fact sheet: Buildings Energy Efficiency, 2006).

To improve the thermal performance of buildings and their energy efficiency, several strategies are now being used depending on the feasibility study and cost analysis of buildings in both the design and operation stage. Improvement of thermal insulation, low emissivity glazing, reduction of air leakage and photovoltaic panels are the major options to improve the performance of the building envelope (Krarti, 2012; Sozer, 2010). The addition of thermal insulation for building surfaces can be a cost-effective measure of improving energy efficiency (Krarti, 2011).
Replacement of windows and use of more energy-efficient windows such as high R value, low emissivity glazing, air tight etc. can be beneficial in the reduction of energy consumption and improving indoor comfort. It is mostly effective when a significant portion of the exposed building surfaces are windows. Reduction of air leakage to lessen significant infiltration load can be other options. Leakage area of the building envelope can be reduced by simple and inexpensive weather stripping techniques. Building integrated photovoltaic panels can generate electricity while absorbing solar radiation and reducing heat gain through the building envelope. Thus this can be another option for improving thermal energy performance of the building envelope.

However, improvement in the efficiency of existing building envelopes of large commercial buildings is not cost effective if expensive modifications are necessary. Energy-efficient building envelope design is suitable for the design stage of the building. Recently, several materials, systems and development practices have been proposed by many researchers for energy efficiency improvement through the design of building envelope (Sozer, 2010; Carlo and Lamberts, 2008; Klaínek, 1996; Carriere, 1999). Spectrally-selective glasses can optimize solar gains and the shading effects of a fenestration system of building. Chromogenic glazing which changes properties automatically depending on temperature and light level conditions is similar to sunglasses that become dark in sunlight. Klaínek et al. (1996) studied the influence of glazing and its shape on energy consumption in commercial buildings, and energy consumption for horizontal and vertical glazing separated by opaque areas. It was reported that for traditional walls with colourless glazing, energy consumption was reduced from 0.92% to 0.78% and 0.18% to 0.16% during summer and winter months respectively. The use of curtain walls can reduce the consumption between 0.3%-0.39%. The energy consumption was higher for vertical discontinuous windows than continuous horizontal windows of the same area. There are several benefits of an energy-efficient high performance glazing system. High performance glazing systems reduce cooling demand in the perimeter areas of the building which leads to fewer requirements for smaller heating, ventilating and air-conditioning (HVAC) plants as well as reduced energy use of cooling. Higher levels of daylight enhance the visual and psychological comfort of occupants. The extra daylight can be utilised in conjunction with daylight-linked electric lighting control to reduce energy use for lighting. Over the life of the building, the reduced energy use will lead to substantial reductions in greenhouse gas emissions.
During the literature review of this research project, the author also visited the energy-efficient eco-building in Griffith University, Nathan campus, to obtain building envelope characteristics that can be considered during design of the building. Some of the pictures of the building envelope have been enclosed in Appendix 1. The building envelope of the eco-building has a significant role in energy efficiency improvement of the building. More specifically, the building’s wall and window construction are critically important for heat gain and later on have a significant effect on cooling energy requirements. Envelope design i.e. wall and window design with different construction materials, affect the internal air temperature of the building. For example, rammed earth walls (80% Sand and clay i.e. clay + binding agent, 10% crusher dust, 5% cement, 5% ash) (Appendix 2) in the eco-centre help to stabilise interior temperatures. Due to their mass, the walls tend to remain cooler in summer and warmer in winter than the temperature of the surrounding air. This helps to control temperature fluctuations. Again, a high level of natural lighting has been achieved inside the building through the use of smart glass (tinted Glass + plastic sandwiched together) which is heat and glare reflective (Appendix 3). This has eliminated the need for artificial lighting during the day and reduced electricity demand in all conditions except for overcast ones. With the correct orientation of the long axis of the building in relation to the passage of the sun overhead, smart glass can contribute to the control of the building temperature. A proper ventilation system within the envelope is another important consideration for the building envelope design. A high level of natural ventilation is achieved through a combination of louvers both at the ground and higher levels. The height difference between the two levels of louvers helps air movement by convection, with the upper louvers opening and closing automatically according to wind direction (Appendix 3). Lower pressure is created on the downwind side of the building and air is sucked through interior spaces to create a ventilation flow.

All of the above design options are closely related with Envelope Thermal Transfer Value (ETTV). Building orientation with appropriate window locations in each orientation, improvement of glazing system, day lighting, building integrated systems, external shading devices, insulation in walls, envelope constructions, U value of wall and windows, are the factors that affect the Envelope Thermal Transfer Value. As the Envelope Thermal Transfer Value includes all the conduction, convection and solar heat gain components of walls and windows, so design of a building envelope with a focus to reduce energy consumption and to
promote the use of energy-efficient systems is a very important decision that can be made during the design stage of new buildings and the operation stage of existing buildings.

2.2.5 Living wall and Green facade systems

Loh (2008) discussed the following three types of internal Living wall system that can improve the thermal and energy performance of a building when they are installed in indoor environment conditions. They are Panel system, Felt system, and Container and trellis system. These systems are shown in Figure 2.2. However, these systems can be used in outdoor Living walls as well. Hopkins and Goodwin (2011) categorised these systems under Green wall or Living wall. It includes Modular Living wall, Vegetated mat wall, and Hybrid system.

![Figure 2.2: Living wall system proposed by Susan Loh (Source: Loh, 2008)](image)

Sometimes plants with a wire, pot or container system are described as Green facade systems whereas modular and vegetated mat wall on building walls are considered as Living wall or Green wall systems in many literatures (Loh, 2008; Hopkins and Goodwin, 2011; Wong et al., 2010; Amir, 2011; Perez et al., 2010). Some applications of Living wall and Green facade are shown in Figures 2.3(a) and (b).
Some countries such as USA, Canada, Singapore and France, have inspired local designers to develop this new technology in building envelope performance improvements. The advantages of using Living wall systems are many. The main benefits of using Living wall systems are increasing the thermal performance of a building, lowering energy consumption and greenhouse gas emissions, reducing the urban heat island effect, positive effects on hydrology, and improving water sensitive urban design (WSUD). In the present research, the concentration would be given on an external Living wall especially a modular Living wall and Green facade system. A modular Living wall is usually pre-grown or can be grown on structures maintaining proper irrigation. The experimental facility has been used in the present research for an external Living wall of modular type.
2.2.6 Rooftop Greenery System

One of the ways of to improve the energy efficiency of a building is to improve its thermal performance. Some researchers analysed the Green roof application in different climate conditions and summarised that a Green roof can reduce energy consumption and keep buildings cool in summer (Santamouris, 2007; Theodosiou, 2009; Sailor et al., 2007; Niachou et al., 2001; Castleton et al., 2010; D’Orazio, 2010). There are many advantages of using Green roofs in buildings. Reduction of energy consumption, cooling of buildings in summer and enhancement of roof life results in longevity of roof and energy efficiency, mitigation of urban heat island effect, retention of the stormwater runoff from roof surface, and reduction of the pollution of urban rainwater runoff, air pollution and noise, all of which are the key focus of using the rooftop Greenery system.

There are three types of Green roof system, as has been mentioned by the Green roof design reference manual (Green roof design resource manual, City of Sydney (2012). A brief description of the three types of Green roof have been summarised from the manual and are outlined below:
An extensive Green roof is the most fundamental form of Green roof. An extensive roof comprises the following components: a waterproof membrane, a root protection layer, a drainage layer, a filter mat, growing medium and finally, vegetation. The root protection layer typically can be combined with the membrane in an extensive Green roof system. It is typically found to have a soil or substrate of no more than 15cm in depth. As a result of the shallow substrate depth, the range of vegetation is limited to low-growing vegetation types including grasses, moss and sedums. The composition of the growing medium is critical in an extensive Green roof system. It is important to avoid an excessively fertile substrate as this will encourage competition amongst vegetation species and may result in an uneven coverage of vegetation. The best method is to have a moderately fertile substrate that maintains a constant coverage yearlong. An extensive Green roof system is commonly used in situations where no additional structural support is desired. Typically, an existing roof will be able to support an extensive system that can weigh up to 100kg/m². However it is important to have some degree of access for maintenance. Extensive Green roofs will require maintenance in the first two years to ensure that the vegetation is stabilised and that there are no weeds. After two years, maintenance is very minimal and may only be required once or twice annually. (Green roof design resource manual, City of Sydney, 2012). An extensive Green roof system is shown in Figure 2.4.

Figure 2.5: Extensive Green roof system of Ford motor company, USA
(Source: Green roof design resource manual, City of Sydney, 2012)
(b) **Intensive Green roof system**

Intensive Green roofing systems are wide-ranging in use. A Green roofing system can support the production of food produce and also provide a public amenity. An intensive roof can even support the production of fruit. Such food production on city rooftops can drastically minimise, if not eliminate, the need to transport fresh produce and thus reduce carbon emissions. The components of an intensive Green roof are the same as all other Green roofs; however, each component requires much more consideration with regards to its form and materiality due to the sensitive relationship between vegetation types, water harvesting and growing mediums. An intensive Green roof needs to balance the quantity of water harvested, the fertility of its substrate and the varieties of vegetation chosen. An intensive green roof system is shown in Figure 2.6.

![Intensive Green roof system, Fukuoka, Japan](image)

**Figure 2.6 : Intensive Green roof system, Fukuoka, Japan**
(Source: Green roof design resource manual, City of Sydney, 2012)

(c) **Semi-extensive Green roof system**

A semi-extensive Green roof is a hybrid of the two systems i.e. made up of extensive and intensive. A semi-extensive roof system is appropriate when the rooftop can be viewed from adjacent buildings but the possibility for access is limited and the structural capacity of the
of deck cannot support an intensive Green roof. A semi-extensive Green roof allows for a slightly deeper substrate depth than a traditional extensive Green roof but it still enjoys the relatively minimal maintenance that an extensive Green roof system has. Due to the relatively deeper substrate, a semi-extensive roof can support a greater variety of vegetation than an extensive Green roof. The selection of vegetation on the roof in a semi-extensive Green roof system is important, as it will directly determine the level of maintenance required to keep the Green roof functioning properly. In general, depending upon the selection of materials, a semi-extensive Green roof can withstand load up to 630 kg/m². Figure 2.7 shows a semi-extensive green roof system.

![Figure 2.7: American society of landscape Architect, Washington, D.C., USA](Source: Green roof design resource manual, City of Sydney, 2012)

The differences between extensive and intensive systems are given in Table 2.1. Figure 2.8 illustrates the layer of extensive and intensive Green roof systems. Extensive Green roof with no public access and intensive Green roof with public access is shown in Figure 2.9.
Table 2.1: Differences between extensive and intensive systems

<table>
<thead>
<tr>
<th>Topics</th>
<th>Extensive</th>
<th>Intensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growing medium</td>
<td>Little or no irrigation</td>
<td>Deep soil, irrigation system</td>
</tr>
<tr>
<td>Insulation</td>
<td>Less insulation compared to intensive</td>
<td>Good</td>
</tr>
<tr>
<td>Weight</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Choice of plant</td>
<td>Limited but studies are ongoing</td>
<td>Large number of plants</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>Comparatively lower than intensive</td>
<td>High</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Suitable for large area</td>
<td>Often accessible</td>
</tr>
<tr>
<td>Storm water retention</td>
<td>Low capacity</td>
<td>High compared to extensive system</td>
</tr>
</tbody>
</table>

Figure 2.8: (a) Extensive (b) Intensive Green roof system
The next section will outline the benefits of using ETTV, Living wall, Green facade and Green roof systems.

### 2.3 Benefits of ETTV

Some of the benefits of using ETTV are presented below.

(a) **Controlling building energy use at the design and use stage**

The building envelope affects the amount of lighting and HVAC requirement of buildings; these are the two largest users of energy in both residential and commercial sectors (Energy Land, 2011). Some of the passive solar design techniques such as orientation, solar shading, window glazing, Living wall and Green roofs affect the ETTV. All of these considerations can be counted during the design stage using the maximum permissible value of ETTV. Hence, during design of any systems mentioned above, ETTV controls the design and
improvement of these systems which leads to building envelope performance, that subsequently improves the electricity and cooling energy consumption of a building. To design a high quality, energy-efficient and cost-effective building, its ETTV, which has been derived from OTTV, is only the first of several factors that can be considered (Chow et al., 2000). Furthermore, the improvement of ETTV through external shading devices and passive solar techniques also improves the energy performance of an existing building.

(b) Climate responsive planning and design

Haase et al. (2006) discussed the advantages of climate responsive building elements such as ventilated facades (VF), Dynamic insulation of walls (DIW), and stated that the thermal transfer value of building envelope i.e. OTTV or ETTV, acts as a driving force for climate-responsive building elements. As weighted average, ETTV is calculated from ETTV of individual orientations, so the change of ETTV of any orientation affects the weighted average value of ETTV. Any type of external shading of walls and windows affects the ETTV of any orientation that in turn affects the total ETTV value of the building. The design of any of these shading techniques has significant focus on the ETTV reduction of an individual orientation as well as total reduction of heat gain and cooling energy requirements, so ETTV assists in climate-responsive planning, design of new and adaptation of existing buildings.

(c) Predict future energy demand

A study in Indonesia indicated that the higher the thermal transfer value, the higher the electricity consumption of single, landed residential buildings (Utama et al., 2011). Nikpour et al. (2011) demonstrated the relationship with the peak energy demand using overall thermal transfer value and ratio of thermal transfer value and day aperture. Chua and Chou (2010a) and Chua and Chou (2011) demonstrated the close relationship of cooling energy estimation and ETTV during the design stage of the building. Predicted energy consumption can therefore be determined from the ETTV of any building. Thus, ETTV provides options for the designer to predict the future energy demand of buildings.
(d) Reduced GHG emissions

A study in Hong Kong indicated that improvement of thermal transfer value reduces the CO$_2$ emissions by around 1166 tons if the buildings are designed following thermal transfer value standards and reducing the thermal transfer value (Sustainability report, 2011). As ETTV deals with the heat gain, which closely correlates with the cooling and electricity energy consumption of the buildings, a reduction of ETTV leads to reduction of energy consumption i.e. reduction of CO$_2$ emissions. Improvements of the building envelope have the potential to reduce GHG emissions from new and existing residential and commercial buildings.

2.4 Benefits of Living wall, Green facade and Green roof systems

The benefits of Living walls and Green roofs can be divided into two major categories: private benefits and public benefits (Hopkins and Goodwin, 2011). Private benefits particularly deal with building owners and occupants, by having an impact on building energy levels, costs and comfort levels, while public benefits are those shared by the wider community and governments, such as mitigation of the Urban Heat Island (UHI) effect or buffering water flow into the stormwater system. Both levels of benefit offer economic advantage, which becomes one of the strongest drivers for the introduction of Green roofs and Living walls. Private benefits include reduced energy consumption and temperature control; noise reduction through insulation; improved indoor air quality; cost reduction by integration with building systems; increased market value; increased usable open space and human comfort; protection to the building structure and direct sustainable action. The public benefits include reducing urban heat island (UHI) effect; air pollution reduction; stormwater management and improved water quality; improved public health and wellbeing; urban agriculture opportunities; integration with landscape, biomass and biodiversity; reclaiming urban wastelands; adapting to climate change and contribution to aesthetics and urban design. Some of the private benefits have been discussed below.
Chapter 2

2.4.1 Reduced energy consumption and temperature control

The amount of shading provided by Living wall, Green facade and Green roof systems can be manipulated. Depending on the plant species selected, planting centres, types of supporting systems and height for the plant to cover, varying densities can be developed from very light 10% cover to very dense 80% cover (Hopkins and Goodwin, 2011). Deciduous planting plays an important role in a Green facade system. These plants usually give shading in summer and shed leaves during winter. Shading the building facade will affect the heating and cooling energy of the air-conditioners, and thus affect the running costs of the building.

Living walls therefore have year-round thermal advantages, with economic and energy-saving benefits. A study by Environment Canada stated 25% saving of cooling demand had been achieved on upper floors under a grass roof (Green Roofs for healthy cities, 2010).

2.4.2 Improved air quality

Vegetation in Living walls and Green roofs captures airborne pollutants such as dust and pollen. Vegetation also filters noxious gases and volatile organic compounds (VOCs) from carpets, furniture and fittings, when Living walls are located inside the building. However, the natural cleaning process is still applicable to outdoor Living walls because external Living walls on building walls act as large air cleaners for the city’s air supply.

2.4.3 Cost reduction by integration of Living wall or Green roof with building systems

Cost reduction by integration with building systems is another advantage of using Living wall and Green roof systems. Integration of different systems in a building has now been studied in different countries. Many buildings were not designed with such a comprehensive design and operational approach. However, building owners and occupiers are now re-thinking the integration of different systems in their buildings, for example, integration of water management and power generation with Green roofs and Living walls can bring economic benefits. City of Melbourne’s CH2 Council House Building, with its 6-star Green Star
certified rating is an excellent example of the cost reduction that is possible with the sustainable integration of all building systems, including Living wall and Green roof. CH2 comprises many parts that work together to heat, cool and power the building, creating a harmonious environment (City of Melbourne, 2011). Solar panels and an extensive Green roof system can play an important role to improve the energy performance of the building. Research conducted at the UFA factory in Berlin, indicates that Green roofs reduce the operating temperature of photovoltaic (PV) systems, thus increasing energy efficiency (Hopkins and Goodwin, 2011). The PV arrays provide shading for the Green roof thus improving the growth of the plants and increasing the number of species. In a word, Greenery cooling helps immensely in improving solar power harvest. Kohler et al (2002) demonstrated that the cooling factor of the Green roof and Living wall could improve the performance of the solar power harvest from 2% to 12% in a combined system of solar panel, Green roof and Living wall. In the case of Australia, Kohler also predicts that the advantage would range from 10% to 25%.

2.4.4 Protection of the building structure

Hopkins and Goodwin (2011) mentioned in their book that studies in Germany indicate that roofs with built-up membrane systems can have a life expectancy of at least twice, and usually three times, as long as usual, or around 50 years. Green roofs can save roof structures from mechanical damage, including the impact of hail and wind-blown dust, ultraviolet radiation that breaks down material and extreme temperature differences. Similarly, Living walls provide protection to building walls. Living walls also improve the longevity of wall life and performance integrity. Protective layers of vegetation on roofs and walls provide enhanced seal and air-tightness of the building.

Some of the public benefits are presented below.

2.4.5 Reducing urban heat island effect

The urban heat island effect is a growing problem in cities. Green facade, Living wall and Green roof systems act as a catalyst to mitigate the urban heat island effect through
evapotranspiration. In this process, one square metre of foliage can evaporate over 0.5 litres of water on a hot day and on an annual basis the same area can evaporate up to 700 litres of water (Hopkins and Goodwin, 2011). A mesoscale atmospheric simulation modelling project for Toronto, conducted by the University of British Columbia, indicated that Green roof coverage of 50% could cool about one-third of the city by 2°C (Hopkins and Goodwin, 2011). Reducing the city’s ambient temperature will reduce the city’s overall energy consumption and also the individual building consumption. The ability to mitigate UHI effects by greening building surfaces without taking up valuable ground space in dense urban areas becomes a powerful driver for the application of Living wall and Green roofs in building.

2.4.6 Air pollution reduction

Green facade, vegetation in Living walls and Green roofs reduce air pollution through the process of photosynthesis. In this process, 155m² of surface area of plants can produce oxygen for one person for 24 hours. Through the natural air filtering process, Living wall and Green roofs can reduce the concentration of toxic gases and particulate matter such as nitrogen dioxide, sulphur dioxide, ozone, carbon monoxide, dust and ash from the air we breathe. It has been estimated that 1m² of grassed roof top removes 0.2kg of airborne particulates from the air each year (Young et al., 2005).

2.4.7 Stormwater management and improved water quality

Stormwater management is an environmental issue in cities worldwide. Living walls and Green roofs can play a significant role in this process and become a major component of the water sensitive urban design (WSUD). At the national urban design forum held in Perth 2007, Graeme Hopkins explained how Green roofs could be used to conserve and recycle water at a household and community level, as an important component of future ‘drought proofing’ (Hopkins, 2007). The principal of cleansing and filtering stormwater that is applicable to WSUD solutions at ground level is similarly applicable to rooftops, even to the extent of rooftop wetlands.
2.4.8 Improved public health and wellbeing

Green outdoor spaces provide direct health benefits to patients in hospitals, clinics and other caring institutions. Hopkins and Goodwin (2011) also mentioned that St Luke International hospital in Tokyo has a garden on its roof top that is accessible to staff which is a welcome relief for them during their available time. People spend a lot of time in commercial buildings, so the productivity of workers can be enhanced due to the presence of Living wall and Green roof systems. For example, monitoring of Melbourne’s CH2 building performance, with its Green facade and natural ventilation, indicated that 75% of occupants of CH2 rate the building as having a positive or neutral effect on productivity, compared with just 25% in relation to their former building (Paevere et al., 2008). The biophysical benefit of visual and physical contact with nature can reduce stress, improve patient recovery rates and provide higher resistance to illness.

2.4.9 Adapting to climate change and carbon footprint

Climate change will bring new challenges for Australian homes. Communities are under threat from an increase in extreme weather with heatwaves, bushfires, floods, cyclones, droughts and storms on the rise. New residential and commercial developments will need to meet sustainability criteria for energy and material use (Reduce your carbon footprint, 2010). In developed city centres, where space for trees, shrubs and lawns is restricted, Living walls and Green roofs can provide an alternative to tackle environmental issues associated with climate change, such as the carbon dioxide and oxygen balance and the escalating UHI effect. Some nations have for some time been actively supporting direct action in relation to Green roofs and Living walls, in order to address climate change. For example, the European city of Stuttgart has been providing similar benefits since 1986 and also supports the implementation of Living walls. It has been claimed that a Living wall just less than 40 square metres in size is as much benefit to the environment as a tree with a crown measuring five metres in diameter (City of Stuttgart, 2009). Mossie (2010) described Green roofs that can cool 16.4 °C per unit area which is slightly behind street trees in terms of heat island mitigating potential. A study in Fifth Creek studio in Victoria stated that Living wall in a trial on building walls can reduce adjacent wall temperature by 9-9.5 °C (Hopkins and Goodwin, 2011).
2.5 Comparative study of different energy efficient methods

The main objective of energy efficiency improvement of buildings by different systems is to reduce the energy consumption of buildings. Improvement in the lighting system, HVAC system and Thermal energy storage system can provide that benefit. The same reduced energy consumption benefit can be achieved through envelope design through ETTV, application of Living wall and Green roof systems. However, the number of benefits of ETTV, Living wall and Green roof systems are significant compared to the improvement through the lighting system, HVAC system and Thermal energy storage system. The main reason is that both significant private and public benefits can be achieved by ETTV, Living wall and Green roofs. These systems are applicable both in the design stage and operation stage, which may not be possible of other systems of the building if there are no alternative options. ETTV, Living wall and Green roof systems are still applicable to new buildings during the design stage and the operation stage to improve the energy performance of the building.

A comparative study of different energy efficient methods for energy efficiency improvement of buildings is shown in Table 2.2.
Table 2.2: Comparative study of different energy efficient methods

<table>
<thead>
<tr>
<th>Approach/Method</th>
<th>Private Benefits</th>
<th>Public benefits</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement in lighting system / Improvement in HVAC system/ Thermal Energy storage system</td>
<td>Less energy consumption</td>
<td>Reduced GHG emission</td>
<td>Significant for private benefits in some cases. However, not significant in many stages for public benefits</td>
</tr>
</tbody>
</table>
| Improvement through the design of building envelope considering ETTV for new building and improvement through the new system application on envelope and roof | ● Less energy consumption  
● Control the building energy use in design stage  
● Encourage climate responsive building planning and design  
● Predict the future energy demand of building for air-conditioning  
● Suggest ways to improve energy efficiency in building, and to take the advantage by limiting the design as the less ETTV the less cooling energy consumption of building, therefore less CO₂ emission | ● Reduced GHG emission  
● Provides options and encourages people to use energy efficient building integrated system (Building integrated Solar panel, Living wall, Green roof) | It’s better to improve the energy efficiency at design stage rather than in operation stage of building. |
| Living wall, Green facade and Green roof systems | ● Less energy consumption  
● Reduced energy consumption and temperature control  
● Noise reduction  
● Improved indoor air quality  
● Cost reduction by integration with building systems  
● Increased market value  
● Increased usable open space and human comfort  
● Protection to the building structure  
● Direct sustainable action | ● Reduced GHG emission  
● Reducing urban heat island (UHI) effect  
● Air pollution reduction  
● Stormwater management and improved water quality  
● Improved public health and well being  
● Urban agriculture opportunities  
● Integration with landscape, biomass and biodiversity  
● Reclaiming urban wastelands; Adapting to climate change; Contribution to aesthetics and urban design | Significant in many stages for both private and public benefits |
The next section will outline the evolution of ETTV in different countries and the study of Living wall, Green facade and Green roof in different countries.

### 2.6 Evolution of OTTV and ETTV in different countries

The concept of OTTV was first adopted by the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) in 1975 (ASHRAE, 1975) and it was updated in 1980 (ANSI/ASHRAE/IES, 1980). A low OTTV value means overall a lower heat gain into the building and therefore, a lower air-conditioning load and less hours of operation of air-conditioning system (Presentation transcript 70.2 Energy Efficiency, 2012). Until now, countries adopting OTTV have been Singapore, Indonesia, Malaysia, Philippines, Thailand, Hong Kong, China, Bahrain, Sri-Lanka, Pakistan, India, Egypt, Japan and some countries of central America including Jamaica and Ivory Coast as shown in Table 2.3 based on available literatures (Devgan et al., 2010; Chua and Chou, 2010a; Chua and Chou, 2011; Lam et al., 2008). However, the study is still continuing all over the world, as maintaining the energy standard as specified by Building Code Boards of corresponding countries is an issue among experts and the Building Code Boards.

Table 2.3: Comparison of OTTV standards of different countries

<table>
<thead>
<tr>
<th>Limit</th>
<th>Singapore</th>
<th>Malaysia</th>
<th>Thailand</th>
<th>Philippines</th>
<th>Jamaica</th>
<th>Hong Kong</th>
<th>Sri Lanka</th>
<th>Pakistan</th>
<th>India</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTTV for wall (W/m²)</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>48</td>
<td>55-67</td>
<td>35-80</td>
<td>19.3</td>
<td>Single value as a function of weight</td>
<td>30.5-52.5 for hot climate</td>
</tr>
<tr>
<td>OTTV for roof (W/m²)</td>
<td>45</td>
<td>25</td>
<td>25</td>
<td>N/A</td>
<td>20</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Chow and Yu (2000) have evaluated the OTTV performance in the case of controlling building energy use with varying models of building ranging between 4000 and 40,000 m³. Yik and Wan (2005) investigated the appropriateness of using the OTTV based on collected data and found that the OTTV performance was not as good, as some discrepancies were
present in solar heat gain calculations of fenestration systems. Chirarattananon and Taveekun (2004) developed an OTTV-based energy estimation model for commercial buildings with a relationship with coefficient of performance of chillers (COP) and analysed the energy consumption of offices, hotels, hospitals and department stores in Thailand.

Researchers around the world have employed OTTV as a performance-based index because it allows designers to use the substitute value of different envelope parameters such as U value, WWR, SC etc. for building heat gain calculation and its relevance to air-conditioned load. Due to more positive relations between total heat gain and heat gain components, and lower diurnal variation in tropical and sub-tropical climates, it is best suited to the tropical and sub-tropical climate zone as mentioned by Chua and Chou (2010b). However, OTTV has been used in different climate zones of the world for heat gain and air-conditioning load estimation. For example, the OTTV-based energy estimation has been studied in different climate zones of China (Yang et al., 2008; Lam et al., 2008). Studies in arid and dry areas such as Bahrain and comparatively cooler areas such as Japan showed a positive relationship between OTTV and energy performance (Radhi, 2009; Hirano et al., 2005). Praditsmanont and Chungpaibulpatana (2008) analysed a case study of a university hall in Thailand using the OTTV method with extensive analysis of heat gain parameters, and evaluated that greater savings and an improved payback period can be obtained if an energy efficient building envelope is applied rather than using a light weight and highly insulated envelope.

Anas Zafirol and Al Hafzan (2010) established the design criteria of two halls of university buildings based on the OTTV and its compliance with the energy efficiency guidelines of the building code of Malaysia. Nikpour et al. (2011) discussed the solar heat gain terms of OTTV with a focus on daylight factors to minimize energy consumption of high rise buildings. Utama et al. (2011) examined the performance of the OTTV in a single, landed residential building and found it suitable for a non-humid ambient condition whereas the OTTV values didn’t show the positive relationship directly with the electricity consumption of high-rise residential buildings due to dominant factors of internal load and some inherent deficiencies of measurement. Recently Chua and Chou (2010a) developed an ETTV equation for Singapore considering the specific values of some parameters and established the relationship of the ETTV with cooling energy estimation. However, it was originally derived from the OTTV, considering only the envelope and internal heat gain. The difference between OTTV
and ETTV is that OTTV considers area of wall, area of fenestration and areas of the exterior of buildings whereas ETTV considers the ratio of fenestration to exterior wall area, as window-to-wall ratio as has been demonstrated by Chou (Performance based standard for energy efficient building, 2004)

Therefore, ETTV is similar to OTTV as it considers the building envelope except the roof. Later, Chua and Chou (2011) evaluated ETTV as a performance-based method for cooling energy estimation of commercial building. Studies on ETTV are now continuing all over the world in estimation of energy consumption of building in various climates. Some studies have come to the conclusion that OTTV may not be only the factor to influence air-conditioned buildings and there is always a necessity to know how OTTV is divided among its three components to identify the impact of OTTV on cooling energy. Devgan et al. (2010) identified some limitations of OTTV as fewer parametric cases have been considered in some analysis (Chan and Chow, 1998; Chow and Chan, 1995), the heat gain has been considered for the entire envelope without considering individual orientations, and there was uncertainty regarding the selection of time period during various seasons to determine OTTV coefficient.

The present heat gain based on ETTV includes only envelope heat gain. However, roof heat gain is significant in the case of low-rise commercial buildings, shopping malls and similar types of buildings. Maneewan et al. (2005) reported that protecting or reducing the heat transfer through the roof is extremely important as it alone represents about 60% of cooling load. Furthermore, average global hourly solar radiation and daily radiation on horizontal surfaces is significant and the intensity of solar radiation is highest on a horizontal plane such as a roof (ASRDH, 2006). Thus, an integrated building heat gain model made of ETTV for envelope and steady-state heat gain by roof, can be investigated to calculate total heat gain of these buildings and to quantify more accurate energy performance. Until now, an ETTV based approach for commercial buildings has not been studied in different climate zones of Australia. In this study, the regression analysis has been performed using hourly heat gain data retrieved from eQUEST simulations for individual orientations to obtain the best energy performance of each orientation. This will contribute to determine the ETTV coefficient and later on, to determine ETTV-based cooling energy estimation for high-rise commercial buildings and ETTV with steady-state heat gain of roof-based cooling energy estimation for low or midrise commercial buildings in the sub-tropical climate of Australia.
Chapter 2

The next section will demonstrate energy efficiency programs and ETTV approach compared to the present methods in building energy consumption analysis in Australia.

2.7 Energy Efficiency Program and ETTV

2.7.1 Energy Efficiency Program for buildings in Australia

In Australia, several rating tools that follow the ENERGY STAR rating are now being used by different agencies, assessors and government for energy consumption analysis. There are several rating tools that use data before designing a new building. In Australia, rating tools that can be used in the design stage of residential buildings to predict the performance are BERS Pro, Firstrate5 and Accurate. These are being used under the House Energy Rating Scheme (HERS) and the Nationwide House Energy Rating Scheme NatHERS (NatHERS software, Nationwide house energy rating scheme, 2011). The NatHERS tool can be used by the house designer to assist in design decision making and therefore, improve the environmental performance of the design (Watson et al., 2001). It is better to assess a building’s thermal performance at the design stage, because it can identify the areas of required improvement. Moreover, it is economical to consider anything before beginning to construct a building. (NatHERS software, Nationwide house energy rating scheme, 2011). A building can be rated before or after it is built. The rating depends on the layout of the home, the construction of its roof, walls, windows and floor, the orientation of windows and shading to the sun's path and local breezes, and how well these suit the local climate. However, energy consumption by hot water systems, lights or household appliances is not part of the rating because those fittings are usually replaced several times during the life of the building. NatHERS uses computer simulations to assess the potential thermal comfort of Australian homes on a scale of zero to 10 stars. The more stars, the less likely the occupants need cooling or heating to stay comfortable. Zero stars means the building shell does practically nothing to reduce the discomfort of hot or cold weather. A 5-star rating indicates good, but not outstanding, thermal performance. Occupants of a 10-star home are unlikely to need any artificial cooling or heating. Houses built in 1990 averaged about 1 star on the NatHERS scale (House energy ratings, 2010).
In April 2010, the Council of Australian Governments (COAG) agreed that the requirement for energy-efficiency in housing under the Building Code of Australia would be raised to 6 stars (Timothy O’Leary, 2012). This higher stringency would be subject to a cost-effectiveness test and undergo a ‘regulatory impact assessment’ before being introduced. A 6-star rating means setting a specific cap on predicted annual energy consumption under the Nationwide House Energy Rating Scheme (NatHERS). This energy target applies to space heating and cooling only and does not involve hot water, lighting or major fixed appliances. COAG said it would require a minimum of six star energy efficiency rating for residential homes and commercial properties built after May 2011 (COAG, Building and construction going Green, 2011). Under the Commercial Building Disclosure (CBD), most sellers or lessors who have office space or commercial buildings of 2,000 square metres or more, will be required to obtain and disclose an up-to-date energy efficiency rating from 1 November 2010 (CBD disclosure, 2010). The National Australian Built Environment Rating System (NABERS) is a national initiative managed by the NSW Department of Environment, Climate Change and Water. NABERS ratings for offices are based on actual data related to the performance of premises over the last 12 months. A rating tool that can be used in the operation stage of commercial buildings to improve the performance is NABERS home, a web-based software that deals with the data of the operation phase of the buildings. For example, it indicates how energy efficiency can be improved. Commercial buildings can use existing building operation data to measure the energy consumption and performance of buildings. To make this real-life performance data comparable with other sites, certain adjustments are made to take into account the specific nature of commercial buildings to make the comparisons relevant and realistic (NABERS, 2010). The Australian Building Code Board (ABCB) developed a number of tools such as glazing calculator, lighting calculator and climate zone map to meet the requirements of the National Construction Code, 2012 (NCC, 2012). The requirement for provision of the energy efficiency of different classes of building is mentioned in section J of NCC and BCA, 2011 series. According to NCC, 2012 and BCA, 2011, commercial office buildings are under class 5. The requirement of ‘R’ value is one of the main focuses of different constructions of building envelope in section ‘J’ in NCC 2012, BCA, 2011. However, the present research focuses on a combined approach made of building constructions, window to wall ratio based on a specific area, thermal conductivity value of walls and windows, solar heat gain coefficient, equivalent temperature value, temperature difference between inside and outside of building. These factors assist to determine Envelope Thermal Transfer Value of buildings. The R value requirement of Green
applications is not mentioned in the present code (BCA, 2011; NCC, 2012). In the present research, the total R value of Green applications has been determined based on available data and used in the Envelope Thermal Transfer Value of buildings.

2.7.2 ETTV approach compared to the present methods in energy consumption analysis of commercial buildings in Australia

The National Australian Built Environment Rating System (NABERS) energy rating tools are now being used by various agencies and consultancy firms in Australia to estimate the energy consumption of commercial buildings during operation (NABERS, 2010). This process of measuring the energy consumption of existing buildings is different from the ETTV because rating tools consider the whole building analysis evaluating the total energy consumption of buildings, including building envelope, lighting, HVAC system, hot water system and other miscellaneous load based on net lettable area or rated area. On the other hand, ETTV deals with the building envelope performance based on building envelope area and miscellaneous load including equipment (Devgan et al., 2010; Chua and Chou, 2010a; Vijayalaxmi, 2011). Again, a rating tool like NABERS is not a predictive tool. Some researchers examined envelope thermal transfer value in case-studied buildings and concluded that envelope thermal transfer value is one of the means of achieving energy efficiency in air conditioned buildings (Chua and Chou, 2010a; Devgan et al., 2010; Chua and Chou, 2011; Vijayalaxmi, 2011). In Australia, different consultancy firms use standard software such as Trane Trace, DesignBuilder or other commercial software to estimate the cooling energy consumption or thermal performance simulation of commercial buildings (Commercial building disclosure, 2010). Commercial software used in Australia (such as Trane Trace, DesignBuilder) for thermal and energy performance simulation has some limitations. These include use of default values that are inappropriate for particular locations. Wasilowski and Reinhart (2009) explained the limitations of commercial software. Tobias (2007) also stated the same limitations of thermal and energy performance simulation. Developing reference building in commercial building software is another disadvantage. The inherent inaccuracy of models in software tools is a barrier to predict the accurate estimation of energy consumption analysis as has been mentioned by Wang et al. (2012). Use of Green applications individually and combined for commercial buildings thermal and energy performance simulation by valid long time experimental data collected from real
experimental setup in Australian climatic condition using Australian native plants, are sometimes inappropriate or sometimes impossible by commercial software. Software such as DesignBuilder and Trane Trace don’t provide options to simulate commercial building using Green applications combined, for example, both Living wall and Green roof. In all cases mentioned above, the mathematical model developed by ETTV provides both the thermal and energy performance estimation options using real experimental data of Green applications and real building data. Therefore, ETTV provides better alternative options to investigate the energy performance of commercial buildings in presence and in absence of Green applications than commercial software.

The advantages of ETTV are significant because it can be used to control the building energy use in design stage, to encourage climate responsive building planning and design and to predict the future energy demand of the building for air-conditioning. It can also suggest ways to improve energy efficiency in the building, and to take advantage by limiting the design as the less ETTV, the less cooling energy consumption of building, therefore less CO₂ emission.

The ETTV has been derived from the OTTV, and it has been one of the simplest methods to predict the future energy demand of a building (Chou et al., 1988). Controlling energy at the design stage is the main focus of the ETTV. The ETTV can be a building design protocol for climate specific building design and planning and will promote an energy management benchmark and a growth in understanding to practice energy-efficient building design amongst engineers and architects. On the other hand, the present ETTV equation provides only the building envelope without considering the heat gain by roof. The roof effect is critically significant for low-rise commercial buildings, shopping malls and similar commercial buildings.
2.8 External Living wall, Green facade and Extensive Green roof systems in different countries

The functional benefits provided by External Living wall and Green facade, and Extensive Green roof, address a number of environmental, economic and social issues arising from increased urbanisation as has been discussed in sections 2.3 and 2.4. External Living wall and Green roofs have an insulation effect that reduces the need for air conditioning to cool buildings. Before discussion of thermal and cooling energy performance of Living wall and Green facade, a brief overview of the Living wall and Green roofs plants used in the external Living wall, Green facade and extensive Green roof systems has been presented briefly.

2.8.1 Plants for Living wall and Green roofs

Hopkins and Goodwin (2011) stated that the selection of plants suitable for Green roofs and Living walls is really important before application on building walls and roofs due to sustainability of plants in different weather conditions. The next section will discuss suitable planting for external Living and external Green roof. This is critically important in investigating thermal and energy performance from experimental studies and later, application in real building.

(a) Plants for external Living wall

Jacklyn et al. (2004) suggested several plant species for Living wall and Green roof systems based on plant type, aspect, maximum height, growth rate, soil type and native or non-native, due to plants’ suitability for surviving for a long period of time. Here, climate was an important consideration. Plant selection has received less attention for Living walls than it has for Green roofs. Again, site-specific considerations, such as aspect, prevailing winds and shading from other structures, make it difficult to prescribe a set palette of plants. Chiang et al. (2009) have compiled a list of suggested plants for vertical greening in the tropics on the basis of trials conducted in Singapore over a six-month period. In general, they recommend using plants that can withstand high temperatures and intense sunlight, as well as low soil
moisture. Plants that provide thick, dense cover and which utilise crassulacean acid metabolism (CAM) were considered preferable. Although Green walls are irrigated, drainage under gravity of narrow containers and a thin media profile means that the rooting substrate can dry out quite quickly. Drought resistant plants are more likely to survive such conditions. Substrate moisture content has been shown to vary from 15 to 45% (v/v) between the top and bottom of a modular Green wall panel, respectively (Cheng et al., 2010).

Dunnett et al. (2008) were against the use of monocultures in Living walls, as these bear a high risk of failure through problems in cultivation or pathogen attack. Instead they recommend employing a range of species and plants that have a clumping rather than an upright growth habit. However, high vigour species should be avoided as they have a tendency to smother neighbouring plants and overload the support structure.

Hopkins and Goodwin (2011) listed some criteria for Living wall plants. These include a fibrous root system, strong stem-to-root connection resistance to wind buffering and good growth habit. Emphasis is placed on a plant’s ability to withstand high temperatures and wind velocities. The suggestion is made that plants found naturally on cliff tops or cliff faces are likely to succeed on a Living wall given certain similarities between the two environments.

(b) Plants for extensive Green roofs

Studies for the selection of plants for extensive Green roofs have been conducted, but predominantly in cool temperature regions of the northern hemisphere (e.g. Durhman et al., 2006, 2007; Getter et al., 2009; Köhler, 2006; Monterusso, et al., 2005; Sendo et al., 2007; Van Woert et al., 2005; Wolf, 2008). Sedum species feature recurrently as the primary choice for these regions. Overseas studies may not be applicable to Australian situations, since the Australian climate is characterised by low rainfall, high evaporation and high year-to-year rainfall variability. This situation, combined with the fact that most of Australia’s capital cities receive seasonal rainfall (i.e. winter-dominant in Melbourne, Adelaide and Perth; summer-dominant in Brisbane and Darwin), creates a challenging environment for plants in exposed situations. A number of textbooks discuss the topic of plant selection for
External Green roofs (e.g. Dunnett et al., 2008; Hopkins and Goodwin, 2011; Snodgrass et al., 2010; Snodgrass et al., 2006; Yok et al., 2008). Low growing plant species that establish quickly to provide good coverage of the substrate are generally recommended. Snodgrass et al. (2006) prescribed an ideal rate of spread of between 15-25 cm in the first year for plants transplanted as plugs and caution against using plants with more aggressive growth rates.

Drought tolerance is another highly desirable trait. The shallow substrate of non-irrigated extensive Green roofs can regularly dry out and drought tolerant species can better maintain adequate vegetation cover during these periods. In Singapore, it has been estimated that a Green roof substrate can be depleted of moisture for four days or more in eight out of 12 months of the year, despite the region’s high rainfall and humidity (Yok et al., 2008). Drought tolerance takes various botanical forms, including succulent leaves, thick leaf cuticles, in-rolled leaf margins or curved leaf surfaces, grey or silver foliage, compact twiggy growth, and small evergreen leaves (Dunnett et al., 2008). Plants that rely on deep taproots for drought tolerance are, however, unsuitable for extensive Green roofs (Snodgrass et al., 2006, 2010).

To provide consistent, long-term vegetation cover, the Green roof planting should be comprised predominantly of hardy succulents or herbaceous perennials. Grasses can also be useful, but regular thatch removal is generally required to reduce fire risk. Plants that have the ability to self-propagate, such as geophytes or self-seeding annuals, can be used for seasonal interest provided that they do not become invasive (Dunnett et al., 2008; Snodgrass et al., 2006).

A root system that gives good anchorage for the plant and which binds the substrate together is desirable to prevent substrate erosion from strong winds or heavy rainfall. This is best achieved by using species with a shallow and dense rooting system, and with stems that root into the substrate as they grow (Dunnett et al., 2008).

Yok et al. (2008) discussed various features of Green roof plants suitable for Singapore and suggested that there would be weather-dependent variables that can affect plant growth rate. Amir et al. (2011) performed a field experiment on Malaysian legume plants that are suitable
for bio-facade application in the climate of Malaysia. Plant selection is a very important issue for Living wall and Green roof performance. Wrong plant selection can lead to various problems in Living wall and Green roof systems. These include pest or disease problems, plant losses, excessive growth, higher maintenance, unattractive structures, poor public perception and inability to provide benefits.

All of the studies relevant to plants suitable for Living wall and Green roof application are continuing all over the world as climate specific studies and one type of plant suitable for a particular climate may not be suitable for another. That requires a field experiment to identify the plant’s thermal performance, its sustainability in different weather conditions and the growth rate of the plant, depending on the type of application required for obtaining thermal and energy performance of the building.

The next section will outline the thermal and cooling energy performance of Living wall, Green facade and Green roof systems as the external Living wall, Green facade and extensive Green roof systems have been studied in the present research.

2.8.2 Thermal energy and cooling energy performance of Living wall and Green Facade

Living walls (internal or external) are emerging technologies that can be used to improve thermal performance of buildings (Loh, 2008). Examples of contemporary Living walls can be found throughout Europe and North America. However, Living walls are most widely adopted in Singapore. The vision of creating a ‘city in a garden’ has led to Singapore focusing much effort into the research and development of Green wall systems that are suited to its tropical climate (Chiang et al., 2009). In Hong Kong, coverage of a concrete wall with modular vegetated panels reduced exterior wall temperatures by up to 16°C in summer (Cheng et al., 2010). At Hort Park in Singapore, various Green wall systems were assessed for their thermal performance by Wong et al. (2010a). Researchers reported differences in external wall temperatures of up to 10°C between vegetated and bare concrete walls.

Kenneth et al. (2010) examined the shading performance of vertical deciduous climbing plant canopies in the UK and demonstrated that 4-6°C temperature reduction of bio-shader wall
had been achieved during the peak summer season. Again, Rahman et al. (2011) analysed thermal performance of bio-facade wall in the tropical environment. However, cooling energy estimation of buildings in the presence of deciduous planting in a Green façade system was absent in their research. Kontoleon and Eumorfopoulou (2010) analysed the thermal performance of plant-covered building walls in Greece and stated that temperature differences between the exterior and interior surfaces of plant-covered walls can be reduced and plant-covered walls can lead to superior thermal comfort for indoor conditions compared to bare walls. Kontoleon and Eumorfopoulou (2010) also examined the reduced energy demand of plant-covered walls compared to bare walls, based on air-conditioned operations in an active thermal zone. However, the required air-conditioned load of a building in the presence of Living wall systems has not been discussed. Wong et al. (2009) used Nephrolepis exaltata (Boston fern) in a vertical greenery system and identified that 50% of ETTV reduction is possible when the results were obtained in TAS simulation in Singapore. However, cooling energy performance in the presence of vertical greenery has not been demonstrated in his study.

Again Wong et al. (2010a) examined eight types of different vertical greenery systems on a building wall based on ambient temperature, wall temperature, surface temperature of greenery and sub-surface temperature of greenery systems. The key findings of Wong et al. (2010a) was ambient temperature reduction and wall surface temperature reduction ranging from 1-9°C and 3.33-5°C respectively. However, the information regarding the annual cooling energy consumption has not been examined in his study. Jim et al. (2011) estimated heat flux of vertical greenery systems on building envelopes and compared the heat flux in north and south facing walls. Jim et al. (2011) opined that vegetation-shielded walls could bring important cooling effects in summer and spring seasons, based on his experimental and mathematical model validation.

2.8.3 Thermal energy and cooling energy performance of Green Roof systems

The functional benefits provided by Extensive Green Roofs (EGR) address a number of environmental, economic and social issues arising from increased urbanisation. EGRs have an insulation effect that reduces the need for air conditioning to cool buildings in summer. In
temperate North America, a cost-benefit analysis of an External Green Roof on a retail store found small, but significant, reductions in energy consumption (Kosareo et al., 2007). In warmer climates, much greater reductions in energy usage are likely to result. Wong et al. (2007) found that in Singapore over 60% of heat gain by a building could be stopped by an external Green roof. In subtropical southern China, less than 2% of the heat gained by an external Green roof during a 24 hr period in summer was retained by the plants and substrate or transferred to the building below. The remainder was lost through evapotranspiration, re-radiated to the atmosphere, or used in photosynthesis (Feng et al., 2010). Implementation of external Green roof on a large scale has the potential to reduce urban heat island (UHI) effects. Susca et al. (2011) reported an average 2°C temperature difference between areas of New York City that have high and low levels of vegetation. External Green roofs with their biological activity, high thermal resistance, and low surface albedo compared with traditional bitumen rooftops, were considered a useful way of combating this UHI effect.

D’Orazio et al. (2010) demonstrated that highly insulated roofs instead of passive cooling strategies (i.e. Green roof strategies) have an adverse effect in internal comfort of buildings and reduces the effectiveness of passive cooling strategies. Green roofs are passive cooling techniques that can reduce absorption of the heat flux of buildings. Gaffin (2005) suggested that Green roofs cool as effectively as the brightest possible roofs with an equivalent albedo of 0.7-0.85 compared to a typical roof with albedo 0.1-0.2. Lui and Minor (2005) performed a field experiment and demonstrated that heat gain through Green roof was reduced to 70-90% in summer.

Alcazar et al. (2005) used a thermal simulation package ESP-r and their results demonstrated that reduction of U value was significant as the U value was reduced from 0.59 to 0.38 with an annual energy saving of 6% in cooling and 0.5% in heating. Getter et al. (2011) performed experiments of extensive Green roof in three different weather conditions (summer, spring and autumn) in the mid-western USA climate and concluded that variations of temperature between Green roof and bare roof were similar in autumn and spring, and the temperature reduction was found to be 5. However, 20°C temperature differences were observed between Green roof and traditional gravel roofs during summer season.
Sailor et al. (2008) identified that the existing mathematical models, developed to calculate energy transfer through the Green roofs, address only the evapotranspiration and time varying soil properties. Later, Sailor et al. developed an Energy balance model to use the code in Energy Plus which is used in the US department of Energy’s simulation program. However, it uses the weather file from World Meteorological Organization, and use of accurate data in Energy Plus for a concurrent year of a specific country except US is an important issue due to conversion of various files, use of suitable plants and different parameters that need to be measured for a long time in a Green roof application from the field experiment.

Kumar and Kaushik (2005) evaluated the performance of Green roof and shading for the thermal performance of buildings, based on LAI of plants in the hot climate of India and concluded that the potential of cooling of the experimental study of his Green roof was 3.02 KWh/day. However, the higher value LAI used in that study may not be appropriate for other plants which have low LAI that will provide less shading effect.

Wong et al. (2003) examined the energy consumption, based on the Roof Thermal Transfer Value (RTTV) of commercial buildings with rooftop gardens in Singapore and demonstrated that 0.6 to 14.5% annual energy consumption can be reduced when shrubs are used on the roof of a hypothetical five-storey commercial building in Singapore. However, skylight-to-roof ratio is an issue for the RTTV equation because there will be no skylight in the case of an opaque roof.

From the authentic literature study of different external Living wall, Green facade and external Green roof systems in different countries, it can be concluded that thermal and cooling energy performance is significant.
2.9 A comparative study regarding the Living wall and Green roof in different countries

According to the literature review of the above sections, this study can be summarised as follows:

All Living wall and Green roof studies are relevant to climate and country specific studies. It is noteworthy that specific plants are suitable for Living wall and Green roof for corresponding countries. Some of the studies are experimental study and some of them are used in real building application. Some country-specific studies include building heat gain and energy consumption. However, all of the studies are separate studies i.e. either Living wall or Green roof application in experimental or in real application. The energy performance of a building in the presence of a combination of both Living wall and Green roof applications has not been studied or discussed extensively in any literature. In addition, how the Living wall and Green roof comply with the building code for reduction of energy consumption has not been investigated in any literature. Again, Envelope Thermal Transfer Value (ETTV) for Living wall applications has only been investigated in Singapore. However, the energy consumption of commercial buildings in the case of Living wall application is still a big issue if the ETTV is reduced and that has not been investigated properly in Singapore. Most of the countries didn’t relate with the associated building energy consumption and code requirement i.e. ETTV. A summary of the literature has been given in Table 2.4. As Envelope thermal transfer value is used to measure the building heat gain and air-conditioning energy consumption of the building, and ETTV can be used as energy efficient building protocol (i.e. envelope code for building), so building heat gain, relevant to energy consumption reduction, can be critically evaluated in the presence of Green applications.
Table 2.4: Living wall and Green Roof application in different countries

<table>
<thead>
<tr>
<th>Countries</th>
<th>Applications</th>
<th>Combination of both Living wall and Green roof in a experimental or real building application</th>
<th>Relationship with ETTV or RTTV of building or with building energy code requirement</th>
<th>Energy consumption of commercial buildings in case of Living wall, Green facade or Green roof and combination of different applications</th>
<th>Some of the most recent references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singapore</td>
<td>Living wall/ Green roof</td>
<td>No</td>
<td>Relationship with ETTV but not relate with code requirement</td>
<td>No</td>
<td>Wong et al., 2010a; Wong et al., 2010b; Wong et al., 2003</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>Living wall/ Green roof</td>
<td>No</td>
<td>Only Roof Thermal Transfer Value</td>
<td>No</td>
<td>Cheng et al., 2010; Jim et al., 2011</td>
</tr>
<tr>
<td>US</td>
<td>Living wall/ Green roof</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Getter et al., 2011; Kosareo et al., 2007; Susca et al., 2011</td>
</tr>
<tr>
<td>Canada</td>
<td>Green roof</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Banting et al., 2005</td>
</tr>
<tr>
<td>Malaysia</td>
<td>Living wall/ Green roof</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Amir et al., 2011</td>
</tr>
<tr>
<td>UK</td>
<td>Living wall/Green roof</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Kenneth et al., 2010</td>
</tr>
<tr>
<td>Brazil</td>
<td>Living wall/Green roof</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Parizotto et al., 2011</td>
</tr>
<tr>
<td>China</td>
<td>Green roof</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Feng et al., 2011</td>
</tr>
<tr>
<td>India</td>
<td>Green roof</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Kumar and Kaushik, (2005)</td>
</tr>
<tr>
<td>Other European Countries</td>
<td>Green roof/ Living wall</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Kontoleon and Eumorfopoulou, 2010; Alcazar and Bass, 2005; D’Orazio et al., 2010</td>
</tr>
<tr>
<td>Australia</td>
<td>Living wall/Green roof</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Williams et al., 2010b</td>
</tr>
</tbody>
</table>
2.10 Living wall, Green facade and Green roof systems in Australia

Some applications of Living wall have been initiated by different organisations in Australia. Architect and landscape architect Hopkins designed and constructed Living walls made of trellis walls of climbing plants to screen air-conditioning ducts in an adjacent public country yard area built over an underground car park, which was probably the first Living wall application in Australia. In Australia, exterior Green walls are a relatively new addition to the urban landscape. Hopkins and Goodwin (2011) presented five case studies of exterior Living walls in Australia, most of which have been completed within the last two years. Among them are Brisbane’s King George Square and the entrance to the Adelaide Zoo, both of which are south-facing Green walls that use modular panel systems. The external modular Living wall applications have been sighted at the Salad bar, Sydney, Adelaide Zoo Eco-science Precinct, Adelaide and King George Square, Brisbane. The internal Living wall applications have been sighted at the Sydney Marriott Hotel, The Gauge, Melbourne, Claude Sebastian, NSW. Internal vegetated mat wall applications have been sighted at the Qantas first class lounge, Sydney. External vegetated mat wall applications have been sighted at the Filmmaker’s Garden, Sydney and Trio Residential Tower, NSW. Green Facade system application has been sighted at the Council House 2 (CH2), Melbourne. All of the applications cover up certain orientations of the building and in some cases small parts of the building wall. Again, all of the applications retrieved from different literature provide little or no information regarding the energy consumption reduction of building. The Living wall application on buildings in the sub-tropical climate of Australia is still in its initial stage due to lack of research on plant selection, plant growth rate, temperature reduction and energy consumption analysis in the presence of Living wall in both experimental and real building application. Experimental results of the performance of Living wall applications in real building application in sub-tropical climates is an issue that will be investigated later on in this study.

One of the earliest and most successful Green roofs in the world is Australian National Parliament House. This house was constructed in 1988 and covered by a carpet of turf grass. There are some examples of intensive Green roofs like Adelaide Zoo entrance precinct, 30 The Bond, NSW, Council House 2 (CH2), Christie Walk Roof Garden, Adelaide, Gymea Bay Garage and Boat Shed, NSW, Hocking Place Bush top, South Australia, Paddington.
Reservoir Gardens, NSW, Water Marque, Sydney, Westbury Apartments, Sydney, Freshwater Place, Melbourne and Ultimo, Sydney. The extensive Green roof applications have been sighted at the Adelaide Zoo Envirodome, The Venny, Melbourne and Kingston High School, Tasmania.

Nicholas Williams identified different grassland species that may be suitable for extensive Green roofs for the temperate climate region in Australia. However, more investigation is required for Green roof substrate depth and water holding capacity for survival of the planting (Williams, 2010a). Melinda Perkins of the Centre of Native Floriculture, University of Queensland, demonstrated some of the features of Sedum plant species and some of the plant species that may be suitable for extensive Green roof systems in Australia (Perkins, 2010).

Most of the research on Green roof applications is in NSW, Victoria and South Australia regions. Very limited studies have been observed in the sub-tropical climate of Australia. Extensive Green roof system applications are comparatively less than intensive Green roof systems. One of the most important issues is that external Living wall and extensive Green roof study in the sub-tropical climate of Australia are still in initial stages due to lack of research in plant suitability and application on real building to perform case studies.

2.11 Research gap

2.11.1 Research gap for the ETTV in Australia

The present trend of using commercial software in Australia for existing buildings by different consultancy firms and Australian government is discussed in Section 2.7. However, the ETTV approach is completely different from present thermal simulation practice as it allows development of mathematical modelling for different climatic conditions and relation to Green applications (i.e. Living wall, Green facade, etc.). The thermal simulation in commercial software does not allow users to perform extensive research studies using different combinations of Green applications made of Australian native plants suitable for different climate conditions. Thermal and energy performance simulation in commercial software available in Australia has some limitations in performing energy estimation using
Green applications. Green applications with Australian native plants and climate specific studies of Green applications are completely different from what is available in software options. Insertion of the collected, surveyed and measured key experimental data in commercial software accurately is a barrier to investigate the simulation and energy-efficient approaches or techniques amongst students and professionals except some qualified experienced experts (Wasilowski and Reinhart, 2009). A survey conducted by some researchers regarding the different simulation programs indicate that usability and information management of interface and integration of intelligent knowledge base is the two crucial factors of choosing appropriate simulation to assess the energy efficiency with compliance of the building code (Attia et al., 2009). The limitations of different commercial software are explained in some literatures (Wang et al., 2012; Tobias, 2007). Attia et al. (2012) stated that the majority of software tools focused on design alternatives after the decision making and overlooked the issue of design alternatives before decision making. A proved benchmark value can overcome this as has been discussed by Attia et al. (2012). Kim et al. (2011) used different techniques of relevant data identification, data analysis and refinement rather than using only simulations to find out the best correlation or combination of different energy systems during the design process of energy-efficient building. Determination of ETTV value using formulation provides comprehensive and flexible options to designers to justify design alternatives for energy efficient building design and complying with the benchmark value at the same time. Escriva et al. (2011) developed several new energy indices of building based on formulation rather than using computer simulations, and proved that the energy indices provide excellent result to assess energy efficiency and to investigate cooling energy consumption analysis for the operation stage of University building. ETTV acts as an energy index in both design and operation stage of building. Use of old climate data for a particular location instead of using recent meteorological data is another disadvantage of thermal and energy performance simulation in commercial software. Appropriate use of customised values instead of default values in software input is a critical issue in thermal and energy performance simulations as has been mentioned in some studies (Wasilowski and Reinhart, 2009; Tobias, 2007). Wang et al. (2012) performed case studies on commercial office buildings using commercial software and concluded that the lack of accuracy of underlying models in simulation tools creates uncertainties in energy consumption estimation and building energy performance prediction. In addition, the reference building used in some commercial software can be developed as the worst building compared to proposed real building to make the proposed building more
energy-efficient. This approach often misleads researchers to make the proposed building more energy efficient using some features compared to reference building, which is sometimes vague and inappropriate, and provides inaccurate and unreal results for the energy efficiency improvement of the building. To overcome all of the above limitations and to obtain more accuracy in energy performance research of commercial buildings, the ETTV approach allows researchers more flexibility compared to other approaches using Green applications. The most recent work relevant to envelope thermal transfer value is reported in some studies (Chua and Chou, 2010a; Devgan et al., 2010; Chua and Chou, 2011). Chua and Chou (2010a; 2011) proved ETTV as a performance based approach to improve the energy performance of commercial buildings and concluded that this energy efficient approach has greater scope to develop energy-efficient buildings using it as a building energy standard index or energy performance standard in different countries.

The ETTV has now been adopted and studied by many countries, and there is a growing demand to study and check the feasibility to adopt ETTV as an energy-efficient building protocol of Australia. This is because the information concerning ETTV relating to various types of building is absent in the Building code of Australia (BCA) (BCA, 2011) and National Construction Code (NCC, 2012). That’s why the determination of ETTV coefficients and the new formulation of ETTV for different orientations of commercial buildings of Australia are very significant to determine the ETTV value for maximum enhancement of the energy efficiency of the building envelope. Again, BCA and NCC provided R values of some building materials in section ‘J’ to satisfy the provision of energy efficiency (BCA, 2011; NCC 2012). However, some researchers criticised the approach of using R or U value and stated that the approach is not appropriate for accurate estimation and a positive relationship with annual energy performance of buildings. Masoso and Grobler (2008) proved and stated that the lower U value doesn’t reflect lower annual energy consumption of buildings. Furthermore, Carlo and Lamberts (2008) proved that U value doesn’t always show a positive relationship with annual energy consumption due to variations of other variables which have an effect on envelope performance of commercial buildings. To overcome the dependence on U value, it is always a better approach to investigate the energy performance with variations of different variables. ETTV accounts different variables for the energy performance improvement of commercial buildings. In the case of solar design techniques, ETTV provides building envelope parameters that allow
researchers to investigate energy efficient passive design techniques. Sozer (2010) proved that passive design techniques have significant impact on the building envelope, which has an effect on energy efficiency improvement of buildings. Another reason behind the present study is to investigate the cooling energy requirement in the case of ETTV adoption. This is because the Australian Institute of Refrigeration and Heating, AIRAH, considers space or floor area for cooling energy estimation and energy management benchmark value, as has been stated in their technical handbook (AIRAH, 2007) whereas ETTV considers the building envelope area. Furthermore, Roof Thermal Transfer value (RTTV) is applicable to a roof with skylights. However, it is not suitable for an opaque roof where there is no skylight (Building and Construction Authority, 2008). So, an ETTV equation with roof heat gain needs to be added to determine total heat gain of buildings.

Overall, the present study will examine:

(a) Coefficient of Envelope Thermal Transfer Value (ETTV) of commercial buildings in the sub-tropical climate of Australia.
(b) Development of a new formulation of ETTV in the presence of external shading devices for different orientations of walls and windows for commercial buildings in the sub-tropical climate of Australia.
(c) Determination of an energy management benchmark value in case of ETTV adoption in the sub-tropical climate of Australia.
(d) Inclusion of the roof effect in an integrated, heat-gain model made of ETTV and steady state heat gain of roof for different types of commercial building i.e. low rise commercial buildings, shopping malls and similar commercial buildings.

2.11.2 Research gap in Living wall, Green facade and Green roof study in sub-tropical climate of Australia

Wong et al. (2009) used Nephrolepis exaltata (Boston fern) in a vertical Greenery system and showed ETTV reduction using TAS simulation and base equation of ETTV in Singapore. However, the predicted cooling energy performance has not been replicated in his study. In addition, the ETTV formulation will be different for Australia, so the ETTV reduction and
cooling energy performance will be different. Again, the plants used in the study may not be suitable for Living wall and Green facade application in Australia. Furthermore, the use of simulation software always has limitations to choose plants and recent climatic data rather than using results from real experimental data made of suitable Living wall and Green facade applications with suitable native plants. There is huge scope for investigation of the combination of Living wall and Green facade, and Living wall and Green roof for thermal and energy performance investigation, that has not been demonstrated in Wong et al. (2009)’s study. Kontoleon and Eumorfopoulou (2010) reported the thermal performance of plant covered wall layers. However, the energy performance of real building in presence of these applications and relationship with ETTV is not extensively discussed. Kumar and Kaushik (2005) demonstrated the thermal and energy performance of Green roof using LAI of plant. However, the higher value LAI used in that study may not be appropriate for Australian native plants suitable for Green applications which have low LAI and that will provide less shading effect. So, different approaches need to be investigated for thermal and cooling energy performance of Green roofs. Wong et al. (2003) examined the energy consumption of a roof top garden, based on RTTV of commercial building, but it has limitations due to the use of RTTV equation because there will be no skylight in the case of an opaque roof. Most of the studies conducted in different countries are individual studies, either Green roof or Living wall suitable for the specific climate. However, no literature demonstrated the combined Living wall and Green roof system or combined Living wall and Green facade system for future application on commercial buildings. Therefore, the research gap can be summarised as follows:

(a) No scientific and in-depth literature regarding the feasibility of using suitable plants in the case of real building application for sub-tropical climate in Australia.

(b) No scientific and in-depth literature regarding how much cooling energy can be saved in the case of application of Living wall or Green facade in combined or individual relevance to ETTV adoption and ETTV-based heat gain and cooling energy estimation in commercial buildings for the sub-tropical climate of Australia.

(c) No scientific and in-depth literature regarding how much energy can be saved in the case of application of combination of both Living wall and Green Roof relevant to ETTV adoption with heat gain consideration for both wall and roof in the sub-tropical climate of Australia.
In Australia, energy estimation of commercial buildings using ETTV with analysis of Green façade and Living wall systems made of Australian native plants in the sub-tropical climate has not been studied. In this present study, the effect of Living wall and Green façade on commercial building cooling energy consumption has been analysed within the sub-tropical climate zone of Australia. Again, cooling energy performance of a combination of Living wall and Green roof application has not been studied in the sub-tropical climate of Australia.

In this study, an integrated building heat gain model comprised of Envelope Thermal Transfer Value (ETTV) of building wall and steady-state heat transfer process of roof has been considered as a performance method for commercial building cooling energy estimation. Then, cooling energy performance, before and after Green roof and Living wall applications, has been analysed in the sub-tropical climate zone of Australia. Thus, the performance of the combination of both Living wall and Green roof system on commercial buildings will be investigated in this study.

To sum up, the present research will address the relationship between two energy efficient approaches, e.g. Living wall and ETTV; Green façade and ETTV; combination of Living wall, Green façade and ETTV; and combination of Living wall, Green Roof and ETTV in a new formulation. This research will investigate the thermal performance of Living wall and Green roof in a real experimental setup and the estimation of energy saving if it is applied to real commercial building application. Estimation of the cooling energy performance i.e. energy saving of commercial buildings by adopting the energy-efficient approaches, will be made in the presence of the following systems (considering before and after the applications) using ETTV:

(a) Only Living wall application
(b) Only Green façade application
(c) Combination of Living wall and Green façade
(d) Combination of Living wall and Green Roof
Conclusion

Overall, the present research will address the energy-efficient approach by ETTV and its close relationship with Living wall, Green facade and Green roof analysis to obtain the best energy performance, and therefore reduce the ETTV and heat gain, and corresponding cooling energy consumption of commercial buildings. ETTV, Living wall, Green facade and Green roof will be the energy-efficient approaches for cooling energy reduction i.e. energy efficiency improvement of both the design stage (newly designed) and operation stage (existing buildings) of buildings.
Chapter 3: Methodology

Summary

In this chapter, the methodology followed to perform this research has been discussed. First, the research approach has been outlined. The methodology has been divided in two stages. In the first stage, the procedure of determining ETTV coefficients, ETTV value and ETTV formulation are discussed. The necessity and benefit of using simulation tool are presented. In the second stage, the methodology for quantification of energy performance using Living wall, Green facade and Green roof have been demonstrated. Mathematical formulation of ETTV, experimental facility and experimental investigation are discussed in detail later on in this chapter.

Before discussing the whole research method, it is appropriate to address the research approach as discussed below in brief.

3.1 Research Approach

To address the research questions mentioned in chapter 1, ETTV formulation was developed and coefficients of ETTV equations were determined. ETTV coefficients have been determined through the analysis of huge number of data sets retrieved from parametric simulated data in eQUEST which is an updated version of DOE 2. The input data relevant to building heat gain parameters have been collected from different consultancy firms, AIRAH handbook (AIRAH, 2007), Australian solar radiation data handbook (ASRDH, 2006) and Bureau of Meteorology (BOM) Australia. Cooling energy performance has been investigated through mathematical modelling using ETTV and simulation in standard software as well.

Many research works have been conducted on thermal performance of Living wall and Green roof using the experimental facilities in different countries. Wong et al. (2010) examined thermal performance of vertical greenery system in Singapore. Kumar and Kaushik (2005) quantified the performance of Green roof using temperature data in hot climate of India and investigated the potential of cooling capacity of Green roof through analytical method. In the present research, relevant data for Living wall and Green roof has been collected from experiment and weather station data. Then ETTV reduction as well as energy performance of
commercial building has been quantified using the Living wall and Green roof data through the analytical method.

As mentioned above, the research method has been divided into two parts. In stage 1, determination and validation of ETTV coefficient, ETTV value, and cooling energy consumption estimation based on ETTV of commercial building have been done. eQUEST energy simulation tool and mathematical models have been used in this stage. A brief overview of eQUEST, has been included in section 3.3 of this chapter. In stage 2, Mathematical investigation has been conducted using ETTV formulation developed in stage 1 and experimental investigation of different Living wall, Green facade and Green roof systems has been done. An experimental facility with both external Living wall in the west facing wall and Green roof have been used to measure different parameters of heat gain. For the Green facade application, mathematical investigation and use of solar radiation data, leaf area index and shading coefficient have been used and heat gain has been calculated using ETTV equations. Then, quantification of energy performance of commercial building using Green applications (e.g., Living wall, Green facade and Green roof systems), have been investigated.

3.2 Methodology to determine ETTV

The methodology to determine the ETTV value has been described below

3.2.1 Weather data analysis

Weather data analysis is an important part of ETTV determination. Location (i.e. latitude and longitude, and climate) affects the ETTV value. So, it is very critical to analyse the weather data for a particular region. Weather data of the sub-tropical climate of Australia have been collected from Bureau of Meteorology (BOM), Australia. Outdoor air temperatures considering the average maximum and average minimum outdoor temperature for any analysis year have been determined based on the available data of meteorological stations.
3.2.2 Building data collection, analysis and input to eQUEST

Collection of data of the existing commercial building in the sub-tropical climate of Australia for reference and input data in eQUEST of model building is the focus in this stage. A data sheet has been prepared based on the type of information required for the ETTV analysis. All of the information relevant to building heat gain parameters associated with ETTV, building elevation, drawing and annual air-conditioning energy consumption, has been collected from different consultancy firms, building owners and facilities management personnel. Using the study of existing building data, initial simulation of these buildings has been done in eQUEST to check whether the determined cooling energy consumption complies with the actual cooling energy consumption of commercial building. Once this is validated, the construction characteristics of these buildings can be taken as a reference for model building. From the characteristics of the existing commercial building, the variation in construction of wall and window has been considered in a later stage, during model building analysis. A summary of the type of information collected in this stage is given below.

General information

1. Type of building
2. Year of construction
3. Plan view of the building
4. Number of floors
5. Floor to floor height
6. Floor area

Information regarding building wall

1. Type of material used in wall
2. Total area of opaque wall
3. Individual area of opaque wall (North, South, East and West orientation)
4. Total area of glazing
5. Window to wall ratio
6. Glass type of window
7. Shading coefficient of window glass
7. Thermal transmittance of wall or U value of wall
8. Thermal transmittance of window or U value of window
9. Solar absorptance of wall surface
10. Solar factor and correction factor considered during design (North, South, East and West orientation)
11. Insulation material used in the wall and thickness of insulation if present
12. Presence of vertical Greenery system in wall (U value of Living wall, Green roof , leaf area index, shading coefficient of plant)

**Information regarding building roof**

1. Type of material used in roof
2. Thermal transmittance of roof or U value of roof
3. Presence of skylight and U value and shading coefficient considered if present

**Other information**

1. Lighting power density
2. Equipment power density
3. Value of sensible heat per person considered during design
4. Value of latent heat per person considered during design
5. No of occupants
6. Total operating hours of the building per week
7. Designed indoor air temperature
8. Annual cooling energy consumption by chiller
9. COP of chiller
10. Annual electricity consumption of the building
11. The number of air changes per hour
12. Total cooling requirement of the building considered during design
13. Total heat load calculated for the building
14. Total cooling load calculated for the building
15. Name of the software used during heat load and cooling load calculation
16. Equivalent temperature difference consideration if present
3.2.3 Parametric simulation in eQUEST

The objective of performing parametric simulation was to retrieve hourly heat gain data of the building for window and wall. The variation of the U value of wall and window construction has been taken from the AIRAH handbook and eQUEST glass library. The parametric simulation has been conducted based on different wall and window construction. The parametric simulation for 11 types of wall and 54 types of window construction has been conducted in eQUEST. During the conduction heat gain by wall, only the variation of wall construction has been considered by keeping the window construction and other inputs the same. Similarly, wall construction has been kept the same during conduction heat gain by window and solar heat gain by window analysis. Based on the construction characteristics, a hypothetical model building has been modelled in eQUEST and parametric simulation has been performed.

3.2.4 Determination of coefficients

Once parametric simulation has been conducted, the next step is the determination of coefficient by regression analysis and mathematical model. The mathematical model used to determine the coefficient has been discussed in Chapter 4. Only positive heat gain values and net heat gain value (i.e., summation of all positive and negative heat gain) have been considered during hourly heat gain data analysis. Then, the total annual heat gain is divided by the total annual air-conditioning hours of operation and building envelope area. Finally, annual total heat gain has been plotted against the U value of wall and window to determine the coefficient of ETTV through regression analysis.

3.2.5 Determination of external shading coefficient

Determination of an external shading coefficient for wall and window for use in the ETTV equation is the main focus of this part. To calculate the external shading coefficient, the total, direct and diffuse radiation effect on window has been computed using mathematical
equation, as has been discussed in Chapter 4. In this case, the fraction of window area exposed to sun plays an important role in the determination of external shading coefficient due to overhang. The external shading coefficient for different vertical shading angle of overhang has been computed and tabulated to use in the ETTV equation. Then the external shading coefficient has been included in the conduction heat gain parts of ETTV equation.

3.2.6 Development of ETTV equation and ETTV value

Development of the ETTV equation for different orientations of wall, and inclusion of external shading coefficient in conduction heat gain part of wall and window, is the first step in this stage. The complete equation of the ETTV for individual orientation has been written in the following format.

\[ \text{ETTV} = \text{Coefficient} \times [\text{Conduction heat gain part of wall}] + \text{Coefficient} \times [\text{Conduction heat gain part of window}] + \text{Coefficient} \times [\text{Solar heat gain part of window}] \]

In presence of external shading coefficient,

\[ \text{ETTV} = \text{Coefficient} \times [\text{Conduction heat gain part of wall}] \times [\text{External shading coefficient for wall}] + \text{Coefficient} \times [\text{Conduction heat gain part of window}] \times [\text{External shading coefficient for window}] + [\text{Solar heat gain part of window}] \]

ETTV equations for north, south, east and west orientation have been established using the above format. Details of the equations are provided in Chapter 4. The ETTV value of individual orientation is weighted averaged to establish the overall value of ETTV.
3.2.7 Inclusion of roof heat gain with ETTV for more accurate estimation

After determination of ETTV value of commercial building, investigation of the cooling energy consumption of building and its relation with envelope and roof heat gain have been examined. ETTV equation and roof heat gain equation made of steady state heat gain, have been developed to make an integrated heat gain model. Then the heat gain model and its relation with cooling energy consumption have been established.

3.2.8 Summary of the method for determination of the ETTV

A summary of the process has been shown in Figure 3.1 for better understanding of the whole method applied to determine coefficient, formulation and value of ETTV and comparative analysis cooling energy estimation.
Gather weather data of sub-tropical climate and determine the diurnal range for which the ETTV equation will be valid

Collect data of existing building of the sub-tropical climate of Australia for reference and input data in eQUEST for model

Select analysis year and perform simulation for base case and parametric simulation for different wall and window construction, and Consider external shading devices in ETTV formulation

Develop ETTV formulation for sub-tropical climate

Relationship with cooling energy to validate coefficients and ETTV estimation

Determination of bench mark ETTV value for sub-tropical climate of Australia

Comparison between ETTV based cooling energy estimation and standard software

Inclusion of roof heat gain in building heat gain model for cooling energy estimation

Perform case study using developed formulation, coefficients and building heat gain model

Figure 3. 1: Summary of the method for determination of the ETTV
3.3 Tools used for simulation

This section will discuss why eQUEST simulation tools have been used in this study and will provide brief information about eQUEST energy simulation tools.

3.3.1 Use of eQUEST

eQUEST is an upgraded version of DOE 2 which is a fully validated (Lawrence Berkeley Laboratory, 1981) and ASHARE certified computer program that predicts the hourly and annual energy use and energy cost of a building (Sullivan and Winkelmann, 1998; Diamond and Hunn, 1981). DOE 2 has been widely accepted by building designers and it has been selected to develop many international building energy-efficiency standards and used by building authorities in different countries around the world. eQUEST provides accurate simulation of alternative materials for building constructions that improve energy efficiency, detailed modelling of building envelope, shading, fenestration, solar heat gain properties of walls and windows, etc. (eQUEST Introductory tutorial v.3.64, 2009).

3.3.2 A brief Overview of eQUEST

eQUEST is a comprehensive and affordable energy simulation tool that provides the option for whole building performance analysis. Whole building analysis recognizes that a building is a combination of many systems and that energy-responsive design is a creative process of integrating the performance of interacting systems, e.g., envelope, fenestration, lighting, HVAC. There are two main parts to eQUEST. The first part is Wizards, which is inclusive both for building creation and Energy Efficiency Measure (EEM) analysis, and the second part includes a detailed Interface including results reporting.

Compared to conventional simulation tools, eQUEST’s Wizards ask comparatively few questions of the user. Combining user input with intelligent dynamic defaults, eQUEST’s Wizards can be used either to conduct schematic or preliminary screening analysis or to provide a momentum in the preparation of more detailed models to be used for further
detailed analysis. eQUEST v.3.64 provides three Wizards; the Schematic Design Wizard (‘SD Wizard’), the Design Development Wizard (‘DD Wizard’), and the Energy Efficiency Measures Wizard (‘EEM Wizard’). The SD Wizard and DD Wizard are used to create building models. The EEM Wizard is used to evaluate building design alternatives (eQUEST Introductory tutorial v.3.64, 2009)

**SD Wizard**

The SD Wizard can only create a single building shell. A building ‘shell’ refers to any area of the building that shares the same footprint shape, HVAC zoning, Ceiling height, envelope construction type and HVAC services.

**DD Wizard**

The DD wizard can be used to create buildings that require multiple shells. The DD Wizard can be used to create many HVAC system type templates and provides more flexibility in assigning them to building areas. For these two reasons, the DD Wizard is more commonly used. Users can start their eQUEST project in either wizard. SD Wizard projects can be converted to the DD Wizard projects at any time. However, DD Wizard projects cannot be converted to an SD Wizard project. eQUEST’s Detailed Interface is a windows-based interface to the DOE-2.2 simulation ‘engine’, the most widely recognized, used, and trusted building simulation tool available today. Compared with the Wizards, the Detailed Interface requires very detailed data (eQUEST Introductory tutorial v.3.64, 2009).

**Parametric and EEM Analysis option**

The principal use for eQUEST is to evaluate the energy performance of various building design alternatives (i.e., design options). This is typically done by simulating at least two designs of a building, one with and one without some specific alternative(s). If this is done via the wizards, eQUEST refers to this as EEM Analysis. If this is done in the Detailed Interface, eQUEST refers to this as Parametric Analysis. Since EEM Analysis uses the EEM
Wizard, it is quicker and easier than Parametric Analysis but provides less detailed control of the design alternatives. Parametric Analysis provides more detailed control of the design alternatives but requires more detailed preparation and input (eQUEST Introductory tutorial v.3.64, 2009).

3.4 Methodology to quantify energy performance

The methodology to quantify energy performance of a building has been divided into two parts. In first part, temperature data has been collected from the Living wall and Green roof experimental setup. In the second part, mathematical investigation has been performed to quantify energy performance in real building application. These are discussed in the next two sections.

3.4.1 Experimental Investigation of Living wall and Green roof

An experimental facility made of Australian native plants has been used to collect temperature data. Much research has been conducted in different countries on Green roof systems and Living wall systems as discussed in the literature review (Chapter 2). Extensive Living wall and extensive Green roof have been used in this facility to perform research on the selection of plants suitable for a sub-tropical climate by Rural Industries Research Development Corporation (RIRDC) of the Australian government with the University of Queensland, Gatton (continued until September 2011). However, the experiment has been performed for the present research from October 2011 to March 2012 during the spring and summer time in this sub-tropical climate. A brief overview of the experimental facility and tools used to measure the temperature data has been discussed in section 3.6.

3.4.2 Mathematical Investigation of Living wall, Green facade and Green roof

Using the temperature data of Living wall and Green roof, the mathematical investigation has been performed to quantify the energy performance of commercial building if external Living
wall and extensive Green roof have been applied on a real building. On the other hand, mathematical investigation of Green facade system to quantify the energy performance in real building application has been performed using suitable planting for sub-tropical climate, leaf area index and solar radiation data. The methodology followed in mathematical and experimental investigation to quantify the energy performance of commercial building has been shown in Figure 3.2.
Figure 3.2: Process of quantification of Energy performance of Commercial building
(by Living wall, Green facade and Green roof)
3.5 Experimental facility

The experimental facility used in this study is a combined Living wall and Green roof setup located at the University of Queensland, Gatton. The structure of the experimental facility used in this study is a fully enclosed structure. The roof area of the structure is 3 m$^2$ with a 3$^0$ pitch. The load-bearing capacity of the structure is 200kg/m$^2$. The site of the facility is on open, flat ground and therefore has minimal shading effect. The location of the facility is convenient to the main water supply. The nearest BOM station is around 1 km away from the location of the facility. There were four such structures that were constructed initially by the authority of the University of Queensland as shown in Figure 3.3. Two structures have the Living wall and Green roof modules and the other two are kept open without Living wall and Green roof, in order to make comparison. The experiment was conducted in two structures. One structure without Living wall and Green roof facility was named as the control shed (Figure 3.4), and the other one with Living wall and Green roof facility was named as Green shed (Figure 3.5).

Figure 3. 3: Initial structure for the Living wall and Green roof experimental setup
Figure 3. 4: Structure without Living wall and Green roof

Figure 3. 5: Structure with Living wall and Green roof

A brief description of construction of the Living wall and Green roof used in the experimental facility has been presented in the following sections.
3.5.1 Description of Living wall

The Living wall system is made up of Elmich Green wall modules, Geotextile liner and Enviroganics Bioganic Earth Green wall mix as shown in Figure 3.6. During the experiment, the following plant species were present in the Living wall system in the facility. These plants have a high survival rate as the experiment was performed after one year of plantation. A detailed description of the plants is given below.

Figure 3.6: Living wall module used in the experimental facility

(a) Plectranthus argentatus

Plectranthus argentatus as shown in Figure 3.7 is a plant species of the mint family. It is native to rocky outcrops and rainforest of the border region of Queensland and New South Wales, Australia. It is a spreading shrub to 100 cm high (25 in), covered with silvery hairs. Its hairy leaves are ovate to broad-ovate, 5–11.5 cm long, 3–5.5 cm wide with crenate margins.
The hairs give the leaves an overall sage Green to silvery colour. The flowers are bluish white.

![Figure 3. 7: Plectranthus argentatus](image)

(b) Plectranthus parviflorus ‘Blue Spires’

This is a herbaceous, soft-wooded perennial type plant. The hardiness zone of Plectranthus parviflorus ranges from 9 to 11. It can sustain hot overhead sun to dappled light. It is capable of handling ordinary soil, enriched soil, mildly acidic to mildly alkaline. Figure 3.8 shows the leaves of Plectranthus parviflorus.

![Figure 3. 8: Plectranthus parviflorus ‘Blue Spires’](image)

(c) Bulbine vagans

This is a perennial herb, 20–60 cm high with thick roots. Leaves of Bulbine vagans are 4-20 channelled, 12–30 cm long and 2–6 mm dia. It erects initially and then procumbent. A picture of Bulbine vagans is shown in Figure 3.9.
3.5.2 Description of Green roof

The Green roof system of the facility consists of the following materials used layer by layer as shown in Figure 3.10

(a) Polyurethane waterproof membrane

This material is made of root-resistant (FLL rated) ethylene vinyl acetate and PVC polymer thermoplastic sheet waterproofing membrane with a proven 30-year, world-wide performance track record. It has tensile strength, excellent elongation and puncture resistance, highly resistant to UV, rot and soil-borne chemicals and microbial organisms as information provided in manual.

(b) 25 mm polystyrene panels

These are polystyrene panels with thickness of 25 mm located just over the membrane.

(c) Elmich Versicell® drainage module

Drainage modules are made of lightweight, high strength, interlocking modules that capture and transport high water volumes and protect the waterproofing membrane.
(d) Elmich Versidrain® 25P drainage sheet

Elmich Versidrain® 25P drainage sheet is a lightweight and cost-effective water management tray. Its function is to store and drain water and to protect the waterproofing membrane. The high water storage capacity of the cells coupled with high discharge capacity ensures effective capillary irrigation, eliminates the possibility of water-logging, reduces irrigation frequency and minimizes fertilizer runoff and usage.

(e) Geotextile

A needle-punch geotextile filter fabric placed onto either VersiCell® or VersiDrain® 25P prevents fine particles in the growing media from entering and causing clogging.

(f) Enviroganics Bioganic Earth Green Roof Mix (150 mm)

It is a lightweight mix made of expanded clay aggregate or vermiculite and other lightweight, high water storage capacity components such as peat moss, composted sawdust and bark fines, coco peat, washed sand, fertilizers and water-retaining crystals.

(g) Enviroganics Envirohydrate Mulch (15 mm)

Enviroganics Envirohydrate mulch has been used in the Green roof system. The mulch has been provided by the supplier Elmich. The thickness of the mulch layer was 15 mm.
The Green roof plants use in the facility include the following:

(a) *Calandrinia balonensis*

*Calandrinia balonensis*, shown in Figure 3.11, is an Australian native herbaceous succulent that originates from the semi-arid regions of central Australia. This selection has been extensively cross-bred to produce a compact plant about 15 cm high x 40 cm wide with...
numerous bright pink-purple flowers about 40 mm in diameter. The stems do not put down runners so it won’t spread throughout the garden.

![Image of Calandrinia balonensis](image)

**Figure 3.11: Calandrinia balonensis**

(b) *Myoporum parvifolium*

*Myoporum* is a genus of about 30 species, of which sixteen are found in Australia. It is a prostrate shrub which can form broad mats of foliage to about 3 metres in diameter. The leaves are linear to narrowly oblong, up to 50 mm long by 5-8 mm wide, with slightly toothed margins. The flowers blossom in the leaf axils in late spring through to early autumn. They are star-shaped, about 75 mm in diameter and may be white or pale pink with purple spots. The flowers are followed by globular shaped fruits. *Myoporum parvifolium* shown in Figure 3.12 is a popular plant in cultivation and is hardy in a range of soils and climates. It provides an excellent spreading groundcover for a sunny position. However, it can become sparsely foliaged. Its hardiness has led to it being used as a root stock for grafting the related *Eremophila* species. Propagation from seed is usually successful without any pre-treatment but germination may be slow. Cuttings of hardened, current season's growth strike easily and this is the preferred method of propagation.
Sedum sexangulare shown in Figure 3.13 is a non-native species. Yok et al. (2008) described the native of Sedum sexangulare as European and Asian. However, it grows well in subtropical climate conditions as has been investigated during the experimental data collection. Sedum sexangulare has six spiral rows of small cylindrical leaves. The yellow flowers appear in summer. It is a vigorous, evergreen perennial with mat-forming growth habit. Stems are fleshy, bearing terminal rosettes of stiff, spoon-shaped, silvery or mid Green leaves, to 3/4 inch long. Bright yellow flowers are star-shaped 1/2 inch across, held on short stems, and borne in flat cymes. Sedums are excellent grown in rock gardens, containers, between stepping stones or in wall niches.
3.6 Plants considered for Green facade system

For mathematical investigation of heat gain and energy performance in commercial building, some of the plants suitable for the Green facade applications have been studied. Among them, Virginia creeper shown in Figure 3.14 has been selected for the analysis of heat gain. The name Parthenocissus quinquefolia is the scientific name for the Virginia creeper. Virginia creeper is a native, fast growing, perennial, woody vine that may climb or trail along the ground. The leaves are compound, containing five leaflets. Leaflets range in size from 2-6 inches and have toothed margins.

![Virginia Creeper](image)

Figure 3. 14: Virginia Creeper (Parthenocissus quinquefolia) on wall

The leaflets are red when they first emerge but turn Green as they mature. In the fall, leaves turn a bright red to maroon colour. The inconspicuous green-coloured flowers are in small clusters during the spring and followed by small clusters of fruit in early summer. Compared to other climbing plants, this plant acts as deciduous plant and is suitable for sub-tropical and temperate climates. The plant has five prolonged leaves. This space-saving plant can be used on bare walls to add interesting greenery. Virginia creeper can be used as a shading vine for buildings on masonry walls. It will not harm the masonry but will keep a building cooler by shading the wall surface during the summer, and shedding leaves during winter.
3.7 Instrumentation and data collection

During the temperature data collection from October 2011 to March 2012, the following tools have been used in the experimental facility to record the temperature data. Ambient temperature was also recorded under a Stevenson screen near the experimental facility site and later compared with ambient temperature measured by the nearest Meteorological station located less than 1 km from the experimental facility. All temperature data has been collected at 30 minutes intervals in measuring points of the experimental facility. A brief overview of instruments is given below.

3.7.1 Tiny Tag Plus 2 Temperature Logger

Tinytag Plus 2 datalogger is a data logger (model TGP450 – model TGP 420; Gemini Data Loggers, UK) shown in Figure 3.15, which is fitted with a fast-response thermistor probe (model PB-5002) placed centrally within each structure, and has been used to record data. This data logger is suitable for measuring temperature of the surface, air and liquid. It can measure temperature only one point at a time, so it was necessary to use a number of data loggers with thermistor probes during the experiment. 12 of these data loggers fitted with thermistor probes were used. Additionally, another type of data logger with a thermometer probe has also been used, as described below.

Figure 3.15: Tiny Tag data logger (left) and when fitted with thermistor probe (right)
3.7.2 YC 747UD data logger with thermometer

Like the Tiny Tag Plus 2 Temperature Logger, YC 747UD is a data logger with thermometer probe that was also used to measure temperature in different points of the experimental facility. In some points, both loggers and thermometer or thermistor probe have been used to measure temperature and make some measurement comparisons. This YC 747UD data logger shown in Figure 3.16 has four channels to record the temperature in 4 points at a same time and is suitable for surface, air and liquid.

Figure 3.16: Data logger YC747UD and thermometer sensor
3.7.3 Surface temperature measuring sensor

The Type K Magnet probe 3M FG/SS lead, fitted with YC 747UD as shown in Figure 3.17, has been used to measure the metal surface temperature of the structure which comparatively provides better results than a regular thermometer or thermistor probe for surface temperature measurement. The magnetic sensor probe is particularly suitable for surface temperature measurement.

![Type K Magnet probe 3M FG/SS lead fitted](image)

Figure 3.17: Type K Magnet probe 3M FG/SS lead fitted

3.7.4 Ambient temperature measurement tool

A special type of ambient temperature sensor shown in Figure 3.18, provided by a laboratory technician from the University of Queensland has been fitted with Tiny Tag Plus 2 logger to measure the ambient temperature near the experimental setup. Then, both sensor and logger have been kept under the Stevenson screen as shown in Figure 3.19, to prevent the sensor from solar radiation and rain because its performance may be affected in the presence of these elements. The Stevenson screen is a special type of screen made of a type of plastic in layers. The Stevenson screen is placed around the sensor with logger to prevent from sun for
the accurate measurement of ambient air temperature. All the recorded ambient temperature data have been compared with Bureau of Meteorology (BOM) station data located nearly less than 1 km from the experimental facility.

Figure 3.18: Sensor fitted with Tiny Tag Plus 2 for ambient temperature measurement

Figure 3.19: Stevenson screen fitted nearly the experimental setup
(Sensor with logger is fitted inside)
Chapter 4: Development of ETTV for Commercial Buildings

Summary

In this chapter, the coefficients of ETTV, formulation of ETTV and ETTV value of commercial buildings have been established. At first, climate data analysis has been conducted for initial checking of the diurnal range of temperature of the sub-tropical climate of Australia for which ETTV formulation has been developed. Then the original ETTV formulation, and the process followed for ETTV formulation have been shown. Energy simulation of model building using a number of input data has been demonstrated subsequently. The hourly heat-gain data retrieved from simulations have been analysed using mathematical models. The coefficients of ETTV have been determined from the regressed value in graphical analysis using the large number of hourly heat gain data. External shading coefficients due to overhang conditions have been determined using solar radiation data. Finally the new formulation of ETTV in presence of external shading devices has been developed using the base equation and developed coefficients. The computed ETTV value showed positive relationship to annual space cooling energy consumption. A comparative study has been conducted among the calculated cooling energy consumption based on ETTV, the actual, and the simulated cooling energy consumptions of commercial buildings in the sub-tropical climate of Australia. In addition, the roof heat gain has been included with ETTV to form an integrated building heat-gain model and accurate measurement of cooling energy consumption. A discussion of the ETTV application on different types of building has been presented.

4.1 Climate, Diurnal variation and relationship of these with ETTV

According to the procedure of determination of ETTV value presented in Chapter 3, climate data analysis is an important part of the process. The ETTV formulation depends on climatic conditions and the diurnal variations have an effect on ETTV formulation. Many studies discussed the climate data before analysis of overall thermal transfer value application (Chua and Chou, 2010a; Yang et al., 2008). Investigation of thermal transfer value of the envelope has been studied in different climate zones of the world. Diurnal range is important as the positive relation of heat gain has an effect on ETTV. Diurnal temperature variations are greatest near the earth’s surface. High desert areas typically have the greatest diurnal temperature variations. Low lying, humid areas typically have the least. Areas like the Snake River Plain (Idaho, USA) can have high temperatures of 38°C (100°F) during a summer day, and then have lower temperature ranging between 5 and 10°C (40-50°F). At the same time, Washington D.C., which is much more humid, has temperature variations of only 8°C.
Chapter 4

The next section will present and analyse the climate data of some cities of sub-tropical Australia.

4.1.1 Climate data analysis of the Sub-tropical Australia

Tropical, sub-tropical and temperate climate is present in different parts of Australia. Usually high, humid summers and warm winters are present in tropical climates. In temperate climates of Australia, mild or warm summers and cold winters are observed. However, warm humid summers and mild winters are observed in the sub-tropical climate zone. The areas of sub-tropical climate zone of Australia lie south of the warm humid zone as shown in Figure 4.1 and 4.2. December, January and February are the summer months, March, April and May are Autumn, June, July and August are the winter season and September, October and November comprise the spring season in sub-tropical areas of Australia. Diurnal variation of temperature is the difference between the highest and the lowest temperature of day. However, to investigate the diurnal range of a sub-tropical climate, the variation of monthly mean maximum and monthly mean minimum ambient temperatures has been considered for five cities, namely; Brisbane, Mackay, Bundaberg, Rockhampton and Gladstone, based on available data from Bureau of Meteorology (BOM), Australia.
Figure 4.1: Different climate zone of Australia
(Source: Commonwealth of Australia 2003, Bureau of Meteorology)

Figure 4.2: Different climate zone of Queensland
(Source: Designing for Queensland’s climate, 2012)
4.1.2 Cooling Degree Days’ consideration for the sub-tropical climate for ETTV and cooling energy estimation

Cooling degree days’ is a unit used to relate the day’s temperature to the energy demand of air-conditioning. Cooling degree days are based on the average daily temperature. The average daily temperature is calculated as:

\[ \text{Average daily temperature} = \frac{\text{maximum daily temperature} + \text{minimum daily temperature}}{2}. \]

If the average daily temperature is above comfort levels, cooling is required. The cooling degree days are determined by the difference between the average daily temperature and the comfort level temperature. If cooling is being considered to a comfort level temperature of 24 degrees, and if the average temperature for a day is 27 degrees, then cooling equivalent to 3 degrees (3 cooling degree days) would be required to maintain a temperature of 24 degrees for that day. However if the average temperature was 21 degrees, then no cooling would be required, so the number of cooling degree days for that day would be zero. In the present research, cooling degree days have been considered based on 24°C, as has been stated in Bureau of Meteorology (BOM), Australia. The number of cooling degree days for sub-tropical climate considered in air-conditioning energy consumption is between 100 -250 degree days as shown in Figure 4.3.

Figure 4.3: Degree days of Australia
(Source: Bureau of Meteorology, BOM 2012)
4.1.3 Diurnal variation in Sub-tropical region of Australia

Mean maximum temperature has been computed from average of maximum outdoor temperature recorded by the Bureau of Meteorology (BOM) of some city areas in the sub-tropical climate of Australia. The same process has been followed for determination of minimum temperature. Analyses of some major cities in Queensland for last three years provide the idea of diurnal variation of temperature in the sub-tropical climate of Australia. From Figure 4.4, Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.8, it has been demonstrated that the variation between mean maximum and mean minimum temperature is around 6-10 °C from January to April, variation is around 8-14 °C from May to September and the range is between 7 and 10 °C for the months October to November. Diurnal variations are more than 10 °C between June and August in four cities, except in Mackay. During the summer and spring months the diurnal variations are relatively lower than in winter months. However, according to Table 4.1 overall variations of diurnal range demonstrate that the variation is not too high compared to high diurnal temperature zones of the world. The lower or medium variation of diurnal range leads to more positive heat gain that relates to ETTV. Chua and Chou stated that ETTV would be best suited in smaller or medium diurnal variation of temperature (Chua and Chou, 2010a; Chua and Chou, 2010b). After determining the diurnal range, it can be concluded that ETTV is suitable for the sub-tropical climate of Australia.

![Figure 4.4: Mean maximum and mean minimum ambient temperature of Brisbane](image-url)
Figure 4. 5: Mean maximum and mean minimum ambient temperature of Mackay

Figure 4. 6: Mean maximum and mean minimum ambient temperature of Bundaberg
Figure 4. 7: Mean maximum and mean minimum ambient temperature of Rockhampton

Figure 4. 8: Mean maximum and mean minimum ambient temperature of Gladstone
4.2 ETTV formulation

Envelope Thermal Transfer Value (ETTV) accounts for the conduction heat gain by wall and window, and solar radiation heat gain by window. Conduction heat gain includes multiplication of equivalent temperature differences for wall, window-to-wall ratio and thermal transmittance of wall. Similarly, conduction heat gain by window includes temperature differences for window, window-to-wall ratio and thermal transmittance of window. The solar heat gain by window due to solar factors and the shading coefficient of window are the main heat-gain elements of ETTV. So, the ETTV of building consists of three main parts:

a) Conduction heat gain by wall  
b) Conduction heat gain by window  
c) Solar heat gain by window

Building design parameters such as orientation of building, wall materials, envelope colour, types of glass, external shading on walls and windows affect the ETTV. Again, climatic conditions such as latitude, ambient temperature and solar radiation have a major influence on ETTV. Indoor air-conditioning also affects the ETTV for HVAC analysis. The ETTV
equation is derived from OTTV and the difference between them has been discussed in section 2.6 of Chapter 2. The original OTTV formulation as per Chou (Performance based standard for energy efficient building, 2004) for any orientation is

\[
\text{OTTV} = ((A_w) \times U_w \times TD_{eq}) + ((A_f / A_o) \times U_f \times \Delta T) + ((A_f / A_o) \times SC \times SF) \quad (4.0)
\]

Area of wall, \( A_w \) can be written as a difference between area of exterior wall and area of fenestration, so the above equation can be written as follows:

\[
\text{OTTV} = ((A_o - A_w) / A_o) \times U_w \times TD_{eq} + ((A_f / A_o) \times U_f \times \Delta T) + ((A_f / A_o) \times SC \times SF) \quad (4.1)
\]

If the ratio of \( A_w / A_o \) is replaced by window to wall ratio, the modified OTTV can be written as:

\[
\text{Modified OTTV} = (1 - \text{WWR}) \times U_w \times TD_{eq} + \text{WWR} \times U_f \times \Delta T + \text{WWR} \times SC \times SF \quad (4.2)
\]

This modified OTTV is termed as ETTV (Chua and Chou, 2010a; Performance based standard for energy efficient building, 2004).

\[
\text{ETTV} = (1 - \text{WWR}) \times U_w \times TD_{eq} + \text{WWR} \times U_f \times \Delta T + \text{WWR} \times SC \times SF \quad (4.3)
\]

Mathematical expression for ETTV calculation is shown in equation (4.4) and is derived from equation (4.1), (4.2) and (4.3). ETTV\(_i\) is for any orientation, therefore a North, South, East or West facing wall can be determined from equation (4.4). The mathematical equation for determining ETTV for the whole building envelope is weighted average ETTV\(_0\) comprised of ETTV of different orientations as has been given in equation (4.5).

\[
\text{ETTV}_i = TD_{eq} \times (1 - \text{WWR})U_w \times \Delta T(\text{WWR})U_f + \text{SF} \times (\text{CF})(\text{WWR})(SC) \quad (4.4)
\]
A brief overview of the ETTV components is presented here.

### 4.2.1 ETTV components

U value of wall and window, window to wall ratio, temperature difference for window heat gain, equivalent temperature difference, solar factor and shading coefficient are the key components of ETTV. The key components have been discussed here briefly.

(a) U value of Wall and Window

U-value of Opaque Wall, $U_w$ (W/m²K) has an effect on the value of ETTV. Less U-value means less heat conduction through an opaque wall hence it results in a lesser amount of ETTV. External walls usually have variable thickness, for example, a brick or concrete wall may have thickness ranging from 125 to 250 mm. Without any thermal insulation the U-value of brick or concrete walls is typically from 2.2 to 2.9 W/m²K depending on the thickness of concrete and the type of surface finish. If insulation materials are attached to the external walls, the amount of U-value decreases significantly as well. The U-value of Fenestration ($U_f$) has an effect on ETTV as well and will be discussed later on in Chapter 4 during the hourly heat gain analysis.

(b) Window to wall ratio, WWR

The area of each envelope in each orientation is one of the important parameters that can influence the amount of heat conduction through opaque walls. However the area of wall depends on the envelope design and it is clear that if the $A_w$ is less, the heat conduction through an opaque wall decreases.

$$A_o = A_w + A_f$$  \hspace{1cm} (4.6)
(4.7)

\[ \text{WWR} = \frac{A_t}{A_0} \]

Where, \( A_0 (m^2) \) is a fixed number. Reduction of the opaque wall area means increasing the area of fenestration. According to the ETTV equation, it is the ratio of window area to gross wall area. It’s clear that with increasing WWR, the amount of ETTV increases.

(c) Temperature difference, \( \Delta T \)

\( \Delta T \) is the temperature difference between exterior and interior design conditions (\(^0\)C). If the differences between outdoor and indoor temperature become less, the heat conduction through the opaque wall becomes less and if the difference is high the heat gain will be high as well.

(d) Equivalent Temperature Difference, \( T_{\text{eq}} \)

Equivalent temperature difference, \( T_{\text{eq}} (^0\text{C}) \), considers both the conduction heat gain due to the temperature difference between the indoor and the outdoor environment, \( DT \) and the effect of solar radiation on opaque surfaces (Kaska and Yumrutas, 2009). If the amount of equivalent temperature increases, the conduction heat gain increases. If \( T_{\text{eq}} \) decreases, the heat conduction through the opaque wall decreases. \( T_{\text{eq}} \) has been determined from parametric simulation of large numbers of data sets of hourly heat gain.

(e) Shading Coefficient (SC)

Among the three components of heat gain in the ETTV equation, solar radiation through the fenestration is the most significant. The building variables controlling solar heat gain are SC and window-to-wall ratio (WWR). Low WWR means low heat gain by window and wall whereas large WWR means high heat gain through window and wall. Sometimes SC is being replaced by the solar heat gain coefficient (SHGC). Solar heat gain coefficient is defined as that fraction of incident solar radiation that actually enters a building through the window.
assembly as heat gain. The shading coefficient (SC) applies to the glazing portion of the window and does not include the effect of frame. It represents the ratio of solar heat gain through the system relative to that through 3mm clear glass at normal incidence. The shading coefficient is expressed as a dimensionless number from 0 to 1. A high shading coefficient means high solar gain, while a low shading coefficient means low solar gain. For any glazing, the SHGC is always lower than the SC. To perform an approximate conversion from SC to SHGC, the SC value is multiplied by 0.87 (Nikpour et al., 2011). The SHGC is influenced by all the same factors as the SC, but since it can be applied to the entire window assembly, the SHGC is also affected by shading from the frame as well as the ratio of glazing and frame. A high coefficient signifies high heat gain, while a low coefficient means low heat gain.

(f) Solar factors

If standard conditions with angles of incidence of 30° or less are assumed, SF (W/m²) is equal to 0.87 times the incident solar intensity. For incident angle greater than 30, solar transmittance will be less than 87 percent (Lam et al., 2005). This is considered acceptable because solar irradiance is relatively small when incident angle is greater than 30°. Solar factors for the four principal orientations are different and will be discussed later in hourly heat gain analysis section.

Some parts of the following sections (Section 4.3 to 4.7) are submitted in journal by Author (Hasan et al., 2012c) and some parts are published partially during candidature (Hasan et al., 2012a; Hasan et al., 2012b)

4.3 Process followed to determine the ETTV Coefficient

4.3.1 Initial analysis of building case studies

Commercial buildings in the sub-tropical climate area of Australia are mostly located in Brisbane, Mackay, Bundaberg, Rockhampton and Gladstone. The process adopted to
determine the coefficients of ETTV as shown in Chapter 3 is based on available weather data, buildings data relevant to heat gain parameters of ETTV and available literature (Muneer Al-Qadhi, 2008; Devgan, 2009; Devgan et al., 2010). Commercial buildings located in these regions are mostly 8-15 story buildings. However, some buildings are taller, ranging from 17 to 20 floors.

Like other energy simulation tools, eQUEST also uses the model representation of the actual building to be simulated. The input deals with representing the building as an abstraction of the reality and this process determines the accuracy of the results. Outputs are the results of simulations, comparison with real energy use data and accuracy checking. Five commercial buildings have been studied and characteristics of five buildings including construction characteristics, air-conditioned operation, annual cooling energy consumption from central air-conditioning unit, occupancy schedule, etc. have been collected and presented in Table 4.2-4.6. The plan view of these buildings has been demonstrated in Figure 4.9. The key point of considering the case study models in this study was to compare the annual cooling energy consumption between the simulated buildings and their actual consumption.

Table 4. 2: Input data for air-conditioning calculation for cases study and model buildings in eQUEST (Collected from consultancy firms)

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HVAC System definitions</strong></td>
<td>Cooling source: Chilled water coils Heating source: Hot water coils Hot water source: Hot water loop System type: Standard VAV with HW reheat Return air path: Ducted</td>
</tr>
<tr>
<td><strong>HVAC zones temperature and Air flows</strong></td>
<td>System (s) : Standard VAV, HW Reheat Thermostat setpoints : Occupied : 70 °F, unoccupied : 82 °F Heating setpoints : Occupied : 72 °F, Unoccupied : 64 °F Design temperatures: Cooling design temperatures: Indoor 70 °F, Supply: 55 °F Heating desing temperatures: Indoor 72 °F, Supply 95 °F Air flows: Minimum Design Flow 0.50 cfm/ft² VAV minimum flow Core : 40 %, Perim: 30%</td>
</tr>
</tbody>
</table>
### HVAC system fans

**Supply Fans**
- System: 1. Standard VAV, HW Reheat
- Supply fan: 3.5 in WG. High
- Fan Flow and OSA: Auto-size Flow (1.15 safety factor)
- Fan Type: Variable Speed Drive

**Return Fans**
- Power and Motor Efficiency: 1.17 in WG high
- Fan Flow: Auto-size
- Fan Type: Variable Speed Drive
- HVAC System # 1 Fan Schedules
  - Operate fans 1 hour before and 1 hour after close

### HVAC Zone heating, Vent and Economisers

- System: Standard VAV, HW Reheat
- Zone Heat Sources and capacities/ Delta T
  - Baseboards: None
  - Heat/Reheat: Hot Water 30°F
- Economiser: Type: Dry bulb temperature, High Limit: 65°F

### HVAC System Hot/Cold Deck Sets

- Cold deck Resets
  - Type: Outside Air Reset
  - Outside: High/Low: 80°F – 60°F
  - Supply Min/Max: 55°F - 65°F

### Cooling Primary Equipment

- CHW Loop: Head 56.6 FT, Design DT: 10°F
- Pump Configuration: Single System Pump(s) only
- Number of System Pumps: 1
- CHW Loop Flow: Constant
- Estimated CHW Load: (Area Served) x Size factor
- Total Chiller Capacity by Type: Type 1 (Auto-sized)
- Chiller Type: Electrical Centrifugal Hermetic
- Condenser Type: Water Cooled
- Compressor: Constant Speed
- Chiller COP: 4.5 - 5.2

---

Table 4. 3: Summary of major input data for operation, internal loads and HVAC system
(For model building and case study buildings)

<table>
<thead>
<tr>
<th>Common characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating hours</td>
<td>08:00 -20:00 h (Monday – Friday), Saturday and Sunday off</td>
</tr>
<tr>
<td>Lighting power density</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>Equipment power density</td>
<td>10 W/m²</td>
</tr>
<tr>
<td>Occupancy density</td>
<td>15 m²/person</td>
</tr>
</tbody>
</table>
Air side system  
Single zone air handler with hot water reheat

Thermostat set points  
21ºC for cooling, 23ºC for heating

Cooling load range for case study building  
800-900 (TR), Screw type Chiller

Cooling load range for model building  
Auto sized

Table 4. 4: Typical construction characteristics of case study buildings

<table>
<thead>
<tr>
<th>Component</th>
<th>U value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>External opaque wall</td>
<td>2.2 W/m²K</td>
<td>12.5 mm ceramic tiles + 200 mm HW concrete + 100 mm airspace + 10 mm plaster board</td>
</tr>
<tr>
<td>Internal opaque wall</td>
<td>2.23 W/m²K</td>
<td>12 mm weather boards + 100 mm airspace + 10 mm gypsum board</td>
</tr>
<tr>
<td>Roof</td>
<td>1.93 W/m²K</td>
<td>10 mm roof membrane + 100 mm concrete slab + 10 mm air space + 10 mm gypsum board</td>
</tr>
<tr>
<td>Floor</td>
<td>1.43 W/m²K</td>
<td>6 mm carpet + 15 mm hair under felt + 100 mm concrete slab</td>
</tr>
</tbody>
</table>

Table 4. 5: Typical window glass construction characteristics of case studied buildings’

<table>
<thead>
<tr>
<th>Building No</th>
<th>Description of fenestration</th>
<th>Shading Coefficient, SC</th>
<th>Uf (W/m² K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Double reflective A, clear L, 12 mm air gap, double pan</td>
<td>0.15</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td>Double reflective A, tint H, 12 mm air gap, double pan</td>
<td>0.22</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>Double reflective B, clear H, 12 mm air gap, double pan</td>
<td>0.27</td>
<td>2.97</td>
</tr>
<tr>
<td>4</td>
<td>Double reflective A, tint M, 12 mm air gap, double pan</td>
<td>0.18</td>
<td>2.76</td>
</tr>
<tr>
<td>5</td>
<td>Double reflective C, tint M, 12 mm air gap, double pan</td>
<td>0.23</td>
<td>2.83</td>
</tr>
</tbody>
</table>

Table 4. 6: Data of case studied and model building

<table>
<thead>
<tr>
<th>Building</th>
<th>Floor Area (m²)</th>
<th>Storey</th>
<th>Envelope Area (m²)</th>
<th>WWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21330</td>
<td>10</td>
<td>6196</td>
<td>0.38</td>
</tr>
<tr>
<td>2</td>
<td>27270</td>
<td>10</td>
<td>7005</td>
<td>0.46</td>
</tr>
<tr>
<td>3</td>
<td>33355</td>
<td>15</td>
<td>9489</td>
<td>0.42</td>
</tr>
<tr>
<td>4</td>
<td>33640</td>
<td>12</td>
<td>8523</td>
<td>0.44</td>
</tr>
<tr>
<td>5</td>
<td>20170</td>
<td>8</td>
<td>5388</td>
<td>0.31</td>
</tr>
<tr>
<td>Model</td>
<td>35000</td>
<td>15</td>
<td>9723</td>
<td>0.43</td>
</tr>
</tbody>
</table>

The eQUEST v.3.64 was used to determine the cooling energy consumption of these buildings and was then compared with the actual cooling energy consumption to validate the estimation by the eQUEST simulation software. A comparison of simulated and actual
cooling energy consumption is shown in Figure 4.10. A sample simulation result regarding annual cooling energy consumption is shown in Figure 4.11.

Figure 4. 9: 3D view of five case-studied buildings in eQUEST v.3.64
Figure 4. 10: Comparison of simulated and actual* cooling energy consumption in case study buildings.

*Actual data collected from some consultancy firms in Australia. Due to confidential agreement, names of consultancy firms are not included in thesis.
Percentage deviation between simulated cooling energy consumption and actual annual cooling energy consumption of the case-studied buildings has been calculated. The deviation varied from 2.5% to 7.5% as shown in Figure 4.12. This variation is considered acceptable and therefore it can be considered that simulation software is able to calculate actual building cooling load. However, it should be noticed that in all cases simulated loads are higher than actual loads. Hourly heat gains from the simulation software will later be used in ETTV analysis.

### 4.3.2 Consideration of data for operation, internal loads and HVAC system

For all analyses of the building in both case-studied and model-building analysis, operating hours for commercial building operations have been considered to be 12 hours of operation. However, this may vary depending on the office schedule, and on Saturday and Sunday it is usually kept off. So, a total of 60 hours per week of operation have been considered. Lighting power density, equipment power density and occupancy density have been collected from different consultancy firms when they have considered during the design stage of HVAC system planning. A single zone air handler with hot water reheat system has been selected during simulation like consultancy firms used during design. Usually design cooling
temperature inside the room is 21-24 °C as per surveyed data; consultancy firms used this temperature during their design of HVAC central systems for air-conditioned office buildings. The number of chiller units in each case study building was two. The capacity of the each chiller unit was within 800-900 TR. All chillers were of the screw type.

4.3.3 Consideration of construction characteristics of buildings

During data collection from the consultancy firms, the construction characteristics have been collected from corresponding building design documentation. All the construction materials in different layers as well as indoor and outdoor thermal resistance have been considered to determine the U value of wall and window.

(a) Construction characteristics of wall

Different types of Masonry wall constructions and frame wall constructions have been considered during parametric simulations of model building analysis. Wall constructions and relevant U value have been taken from the AIRAH Technical handbook (AIRAH, 2007) to investigate heat gain in Australian climatic conditions.

(b) Construction characteristics of window

All the window glasses of the case-study buildings were reflective glasses. Heat generated inside the building tends to stay within the building when the windows are made from reflective glass. Conversely, heat from outside sources tends to stay outside due to reflected radiation by reflective glasses. This keeps the building cool in summer. Some structures with reflective glass may be able to scale down or eliminate climate control systems through the use of reflective glass and other passive measures, while others need to run these systems less frequently, saving money and helping the environment out at the same time. A classic use of reflective glass in building facades is gaining popularity around the world. Using reflective glass can cut down on operating costs over the building's lifetime, in addition to making the interior more pleasant to work in. The precise finish used on reflective glass varies. There are
a number of options available; some reflective glasses are tinted and some are clear double glazed. Different types of reflective glass with different U value, transmissibility and solar heat gain coefficients have been chosen during the parametric simulation of model building analysis. A set of different glass types has been taken from eQUEST v.3.64 glass library.

4.4 Energy simulation and analysis of model building

Pedrini et al. (2002) described a method for building models which is divided into three stages

(a) Simulation from building design plans and documentation
(b) Walk through and audit
(c) End use energy measurements

Some combinations of simulation based on design plan, survey data and end use energy consumption have been accumulated to perform this study. In the present study, the actual energy consumption of case-studied buildings has been compared with simulated energy consumption. The first model was created in eQUEST using all information relevant to building heat gain parameters, air-conditioning energy data and construction characteristics of actual buildings. For simplification of the simulation, a rectangular shaped, hypothetical model building was created as shown in Figure 4.13 based on the characteristics of existing buildings. All the orientations of the building i.e., north, south and east and west facing, were kept unshaded throughout the year. The model building can be representative of commercial buildings in the sub-tropical climate of Australia. Construction characteristics have been varied in eQUEST for each parametric simulation. The construction characteristics have been selected from the Australian Institute of Refrigeration and Heating (AIRAH) handbook and eQUEST glass library.
Eleven types of wall construction and 54 types of window construction have been used in eQUEST for hypothetical building model simulation. Parametric simulations were run for various constructions of walls and windows. Hourly heat gain for wall conduction, window conduction and window heat gain due to solar radiation has been retrieved from simulated results in each case. The unit (Btu/hr) has been converted to SI unit during analysis in Excel.
files. Hourly solar radiation data have been selected as an input to eQUEST for the analysis year 2011.

4.4.1 Step-by-Step Procedure of Model Building Simulation

The simulation in eQUEST for a model building requires different data in 41 stages or screen wizard. Some of the screen shots of the steps have been shown in Appendix 4. Appendix 5 demonstrates conversion of Schematic diagram (SD) Wizard to Detailed data (DD) edit Wizard and screenshots of some the steps. For details of the hourly results for the base case, some screen shots have been added in Appendix 6. some of the screen shots of parametric simulations have been added in Appendix 7.

4.4.2 Analysis of Hourly Heat Gain

As ETTV deals with the conduction heat gain of wall, conduction heat gain of window and solar heat gain by window, so the three options; ‘Conduction heat gain through external wall’, ‘Conduction heat gain through window’ and ‘Solar radiation heat gain’, have been selected for ‘hourly report block’ in eQUEST. The equations (4.8), (4.9) and (4.10) (Devagan et al., 2010) have been used to determine wall conduction heat gain, window conduction heat gain and heat gain after solar radiation by window respectively for all four orientations of hypothetical model building.

Generally, heat gain is positive during the day and negative during night time when outside temperatures are lower than indoor. In the sub-tropical climate of Australia, the observed heat gain was positive during autumn, summer and spring months whereas negative heat gain was observed during winter months (June, July and August). The values of $\sum H_{wi}$, $\sum H_{gi}$ and $\sum H_{si}$ are a summation of heat gain for 8760 hours in a year. Two analyses have been done; in the first analysis the net heat gain has been considered by summing all positive and negative values. In the second analysis, only positive heat gain has been considered, so only positive values have been counted.
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\[ Q_{wi} = \frac{\sum H_{wi}}{(N \times A_{wi})} \quad (4.8) \]

\[ Q_{gi} = \frac{\sum H_{gi}}{(N \times A_{gi})} \quad (4.9) \]

\[ Q_{si} = \frac{\sum H_{si}}{(N \times A_{si})} \quad (4.10) \]

\( Q_{wi} \), \( Q_{gi} \) and \( Q_{si} \) are conduction heat gain by wall, window and solar gain by window respectively, calculated based on air conditioned hours and the corresponding area of building envelope. These values are dependent on the characteristics of wall and window constructions. Different types of constructions were used during parametric simulation of the model building (Table 4.7).

Table 4.7: Typical construction characteristics

<table>
<thead>
<tr>
<th>Component</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>External opaque wall</td>
<td>U value: 0.5-3.9 W/m²K (Construction details with U value collected AIRAH Handbook 2007, p 152-155)</td>
</tr>
<tr>
<td>Window glass</td>
<td>U value: 1.96-3.71 W/m²K, SC: 0.15-0.96, Type: Double clear/tint/reflective/low-e (Detailed information collected from eQUEST v.3.64 glass library)</td>
</tr>
</tbody>
</table>

Three coefficients TD\(_{eq}\), \( \Delta T \) and SF have been computed using equations (4.11), (4.12) and (4.13) respectively based on hourly data analysis in eQUEST.

\[ Q_{wi} = U_1 \times x \times TD_{eq} \quad (4.11) \]

\[ Q_{gi} = U_1 \times \Delta T \quad (4.12) \]

\[ Q_{si} = SC_f \times SF \quad (4.13) \]
The value of $U_w$ (W/m$^2$K), $U_f$ (W/m$^2$K) and $SC_f$ were varied in each parametric run to achieve the predicted values of $TD_{eq}$ ($^0$K), $\Delta T$ ($^0$K) and SF (W/m$^2$), using equations (4.11), (4.12) and (4.13) (Devgan et al., 2010).

Solar factors are dependent on orientations of window, SC and transmissibility and absorptivity of glass. The specification of the fenestration system varies as per individual countries’ standard specification.

So, to determine the ETTV coefficient, the first thing required is the completion model building simulation for base case and parametric simulation for different wall and window construction. Finally, all of the hourly heat gain results have accumulated to obtain the coefficient using equations (4.8) – (4.13).

### 4.4.3 Determination of External Shading Coefficient for walls and windows

There are many ways to control the amount of sunlight that is admitted into a building. In warm climates, excessive solar gain may result in high cooling energy consumption whereas in cold and temperate climates, winter sun entering windows can positively contribute to passive solar heating. Natural illumination can improve control of day lighting in all climates.

Well-designed shading devices can dramatically reduce building peak heat gain and cooling requirements and improve the natural lighting quality of building interiors. Shading devices can also improve users’ visual comfort by controlling glare and reducing contrast ratios. This often leads to increased satisfaction and productivity (Sun control and shading devices, 2008). Shading devices offer the opportunity of differentiating one building facade from another. This can provide interest and human scale to an otherwise undistinguished design.

During cooling seasons, external window shading is an excellent way to prevent unwanted solar heat gain from entering a conditioned space. Shading can be provided by natural landscaping or by building elements such as awnings, overhangs, and trellises. The design of effective shading devices will depend on the solar orientation of a particular building facade.
For example, simple fixed overhangs are very effective at shading south-facing windows in the summer when sun angles are high. However, the same horizontal device is ineffective at blocking low afternoon sun from entering west-facing windows during peak heat gain periods in the summer.

The ASHRAE 90.1 standard allows credit for permanent overhangs that provide significant shading. To investigate the effect of external shading coefficient on windows, the basic concept of shading coefficient has been considered. In ETTV formula, the external shading coefficient can be added in the following form (Building and Construction Authority, 2008; BCA, 2011; Nikpour et al., 2011)

\[ T_{sc} = SC_1 \times SC_2 \]  \hspace{1cm} (4.14)

In equation (4.14), \( T_{sc} \) is the total shading coefficient of the fenestration system, \( SC_1 \) is the shading coefficient of glass or effective shading coefficient of glass with solar control film; \( SC_2 \) is the effective shading coefficient of external shading devices.

The next section will present the detailed analysis of the effect of external shading devices on ETTV.

**Influence of external shading devices on ETTV**

Window overhang has an influence on ETTV as overhang provides a shading effect on windows. The position of overhang and its inclination with wall affect the heat gain of both window and wall. The overhang acts as an external shading device if it is located on the wall at an appropriate distance at the top of the window, where the window is located between the upper and lower portion of wall. Both the inclined overhang and straight overhang are used as shown in Figure 4.14. In both cases, the window is located at a certain distance, \( h_1 \), from the upper portion of wall. The fraction of window area exposed to sun is denoted as \( G_1 \). The value of \( G_1 \) for inclined overhang and straight overhang can be determined from equations (4.15) and (4.16) (Devgan et al., 2010). The horizontal shading angle \( \varphi_1 \) is zero for straight
overhang and therefore only vertical shading angle $\theta_1$ is considered. The external shading coefficients for windows ($E_{sc}$) and walls ($E_{scw}$) for different orientations are determined by using equations (4.17) and (4.18) (Devgan et al., 2010; Building and Construction Authority, 2004)

$$G_1 = 1 - \frac{b}{h} \left( \cos \phi \tan \theta_1 + \sin \phi \right)$$  \hspace{1cm} (4.15)

$$G_2 = 1 - \frac{b}{h} (\tan \theta_2)$$  \hspace{1cm} (4.16)

$$E_{sc} = \frac{\Sigma(G_i x I_d + l_d)/\Sigma I_r}{h}$$ \hspace{1cm} (4.17)

$$E_{scw} = \frac{[E_{sc} x h] - (E_{sc1} x h_1)]/h_2}{h_2}$$ \hspace{1cm} (4.18)

![Diagram](image)

Figure 4.14: (a) Inclined (b) Straight overhang located at certain distance from window (Source: Building and Construction Authority, 2004).

Yearly direct and diffuse solar radiation on horizontal plane for year 2006 has been considered using the Australian Solar Radiation Data Handbook, (ASRDH, 2006). Using the data from Solar Radiation Data Handbook, direct radiation on a vertical plane for the year 2006 has been calculated by a model equation developed by Keller and Costa (Keller and Costa, 2011). Due to the unavailability of data in the Australian Solar Radiation Data Handbook for the year 2010, data for 2012 was collected from Bureau of Meteorology.
(BOM), Australia. All solar intensity values for the year 2010 have been computed based on Keller and Costa’s model using the data from BOM. Later these values are compared with the mathematically calculated value of the year 2006 (Table 4.8). The purpose of the two analyses years was to examine whether any variation in solar radiation data affects the computation of external shading coefficient if the variation is significant.

Table 4. 8: Comparison of total irradiation on vertical surface

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Yearly (2006) average total radiation on vertical plane (W/m²)</th>
<th>Yearly (2010) average total radiation on vertical plane (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>328</td>
<td>330</td>
</tr>
<tr>
<td>South</td>
<td>109</td>
<td>113</td>
</tr>
<tr>
<td>East</td>
<td>195</td>
<td>202</td>
</tr>
<tr>
<td>West</td>
<td>221</td>
<td>229</td>
</tr>
</tbody>
</table>

The external shading coefficient \( E_{sc} \) for window and wall due to straight or inclined overhang can be obtained from the relationship stated in equation (4.17). However, \( E_{sc} \) of wall area \((h_1 \times w)\) is not same as window area \((h_2 \times w)\). So, external shading coefficient for wall, \( E_{sc1} \) has been determined from linear interpolation after determining the value of \( E_{sc} \) (Building and Construction Authority, 2004). Finally, the external shading coefficient for window, \( E_{scw} \) has been determined from equation (4.18). The whole process of this analysis is shown in Figure 4.15.
In this study, for different types of horizontal and vertical shading components, the value of \( E_{sc1} \) and \( E_{scw} \) has been calculated for \( \phi_1 = 0^\circ, 10^\circ, 20^\circ, 30^\circ, 40^\circ \) and \( 50^\circ \) with corresponding \( P/h \) value range of 0.5 to 1.5. Computed values of \( E_{sc1} \) and \( E_{scw} \) have been presented in tabular format for North, South, East and West orientation in Table 4.9 and Table 4.10 respectively.

Table 4. 9: External shading coefficient for window due to horizontal shading device

<table>
<thead>
<tr>
<th>P/h</th>
<th>Orientation</th>
<th>( 0^\circ )</th>
<th>( 10^\circ )</th>
<th>( 20^\circ )</th>
<th>( 30^\circ )</th>
<th>( 40^\circ )</th>
<th>( 50^\circ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>N</td>
<td>0.872</td>
<td>0.923</td>
<td>0.841</td>
<td>0.799</td>
<td>0.708</td>
<td>0.585</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.493</td>
<td>0.957</td>
<td>0.911</td>
<td>0.888</td>
<td>0.837</td>
<td>0.769</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>0.754</td>
<td>0.933</td>
<td>0.863</td>
<td>0.827</td>
<td>0.748</td>
<td>0.643</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>0.750</td>
<td>0.934</td>
<td>0.864</td>
<td>0.827</td>
<td>0.749</td>
<td>0.644</td>
</tr>
<tr>
<td>1</td>
<td>N</td>
<td>0.872</td>
<td>0.846</td>
<td>0.683</td>
<td>0.548</td>
<td>0.343</td>
<td>0.193</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.493</td>
<td>0.914</td>
<td>0.823</td>
<td>0.748</td>
<td>0.635</td>
<td>0.551</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>0.753</td>
<td>0.867</td>
<td>0.727</td>
<td>0.610</td>
<td>0.434</td>
<td>0.305</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>0.750</td>
<td>0.868</td>
<td>0.728</td>
<td>0.612</td>
<td>0.437</td>
<td>0.308</td>
</tr>
<tr>
<td>1.5</td>
<td>N</td>
<td>0.872</td>
<td>0.770</td>
<td>0.525</td>
<td>0.297</td>
<td>0.283</td>
<td>0.711</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.493</td>
<td>0.872</td>
<td>0.735</td>
<td>0.608</td>
<td>0.601</td>
<td>0.839</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>0.753</td>
<td>0.802</td>
<td>0.592</td>
<td>0.395</td>
<td>0.382</td>
<td>0.751</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>0.750</td>
<td>0.803</td>
<td>0.592</td>
<td>0.398</td>
<td>0.384</td>
<td>0.752</td>
</tr>
</tbody>
</table>
Table 4. 10: External shading coefficient for wall due to horizontal shading device

<table>
<thead>
<tr>
<th>P/h</th>
<th>Orientation</th>
<th>0°</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>N</td>
<td>0.130</td>
<td>0.207</td>
<td>0.288</td>
<td>0.381</td>
<td>0.495</td>
<td>0.648</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.516</td>
<td>0.558</td>
<td>0.604</td>
<td>0.655</td>
<td>0.719</td>
<td>0.804</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>0.251</td>
<td>0.317</td>
<td>0.387</td>
<td>0.467</td>
<td>0.565</td>
<td>0.697</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>0.254</td>
<td>0.319</td>
<td>0.389</td>
<td>0.469</td>
<td>0.567</td>
<td>0.698</td>
</tr>
<tr>
<td>1</td>
<td>N</td>
<td>0.130</td>
<td>0.283</td>
<td>0.446</td>
<td>0.632</td>
<td>0.859</td>
<td>0.966</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.516</td>
<td>0.601</td>
<td>0.693</td>
<td>0.795</td>
<td>0.922</td>
<td>0.992</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>0.251</td>
<td>0.383</td>
<td>0.523</td>
<td>0.683</td>
<td>0.879</td>
<td>0.995</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>0.254</td>
<td>0.385</td>
<td>0.525</td>
<td>0.684</td>
<td>0.879</td>
<td>0.998</td>
</tr>
<tr>
<td>1.5</td>
<td>N</td>
<td>0.130</td>
<td>0.360</td>
<td>0.605</td>
<td>0.883</td>
<td>0.991</td>
<td>0.995</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.516</td>
<td>0.644</td>
<td>0.780</td>
<td>0.935</td>
<td>0.993</td>
<td>0.938</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>0.251</td>
<td>0.449</td>
<td>0.659</td>
<td>0.899</td>
<td>0.996</td>
<td>0.589</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>0.254</td>
<td>0.451</td>
<td>0.661</td>
<td>0.900</td>
<td>0.998</td>
<td>0.586</td>
</tr>
</tbody>
</table>

4.5 Results

4.5.1 Heat gain and its relationship to the ETTV coefficient

A linear relationship is usually observed between U value of wall and heat gain of wall in the wall conduction heat gain section of ETTV equation (equations 4.4 and 4.11) due to the dependence of wall conduction heat gain on U value of wall, solar absorptance and the equivalent temperature difference. Generally, during hourly analysis of conduction heat gain, it has been observed that the sum of all positive and negative gains (i.e., net heat gain) has a positive relation with U value of wall. Results presented in Figure 4.16 and Figure 4.17 showed a positive linear relationship between heat gain and U value of wall. Both the net heat gain and only positive heat gains by wall conduction showed a positive relationship with U value of wall.
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Figure 4. 16: Correlation of conduction heat gain and U value of wall (net heat gain)

Figure 4. 17: Correlation of conduction heat gain and U value of wall (positive gain)

However, the results provided two different values in each case i.e., net heat gain and only positive gains. It means that there are two data points due to the consideration of net and positive gains for each value of U. So, the average value needs to be considered to achieve a better prediction of heat gain due to wall conduction. The heat gain by north and west facing wall is linear with U value of these walls as shown in Figure 4.18 for north and west facing orientation.
However, when all the data i.e., net and positive heat gain, is considered for south and east facing walls, then the relationship between the heat gain and U value of these walls provide more accurate results if the polynomial relation of regressed value has been considered instead of the linear value as shown in Figure 4.19. Therefore, the relationships between heat gain and U value of south and east walls are polynomial instead of linear. The negative part of the polynomial of south facing wall denotes that negative heat gain has an effect on south facing wall. However, the coefficient of polynomial in second order term for south and east facing is comparatively small due to low diurnal variation of temperature. So the reversal of heat flow will have less effect on heat gain in the case of wall conduction. However, the reversal of heat flow i.e., negative heat gain, has an effect on net heat gain calculation for any analysis year. The two coefficients $TD_{eq}$ and $\alpha$, become one coefficient, $C_{NW}$ for north and west facing walls. The coefficients $C_S$ and $C_E$ have been used for both south and east facing walls respectively.

![Figure 4.18: Correlation of conduction heat gain and U value of north and west facing wall (considering net and positive heat gain)](image-url)

\[
H_N = 3.903 \times U_w
\]
\[
H_W = 6.299 \times U_w
\]
Figure 4.19: Correlation of conduction heat gain and U value of south and east facing wall (considering net and positive heat gain)

Figure 4.20: Correlation of conduction heat gain by window and U value of window (considering net and positive heat gain)

Figure 4.20 represents the relationship between conduction heat gain by window and U value of fenestration, \( U_f \). For all windows of all orientations, the coefficients determined from linear regression for window conduction heat gain are almost the same. Although, it was
predicted that the relationship would be linear from mathematical heat gain analysis, the relationship was found linear within the range 1.96 to 2.3. So, a second order polynomial has been considered to express the relationship. The polynomial equation is almost the same in all orientations, as has been found in the analysis. It has been concluded that conduction heat gain by window is not influenced by orientations. The value of ΔT consists of two coefficients; C_{DT}, a second order term and D_{DT}, a linear term.

\[ H_N = 346 \times SC \]
\[ H_S = 107 \times SC \]
\[ H_E = 185 \times SC \]
\[ H_W = 216 \times SC \]

![Figure 4.21: Correlation of radiation heat gain by window and SC value of window](image)

From Figure 4.21, it has been observed that heat gain by windows due to solar factors has a linear relationship with shading coefficient of glass although some variations are encountered with low shading coefficient ranging 0.15 to 0.4. The solar factor is completely dependent on the orientation of window. For the shading coefficient values range 0.5 to 0.9, it showed a linear relationship with radiation heat gain by window.

**4.5.2 The ETTV formulation for the sub-tropical climate of Australia**

Chua and Chou (2010a) developed the initial equation of ETTV (equation 4.4). The new formulations (4.19-4.29) of ETTV for commercial building in sub-tropical climate would be based on equation (4.4). Coefficients (Table 4.11) of ETTV formulation have been determined from linear regression in Figures 4.16-4.21.
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Table 4.11: Determined Coefficient of ETTV for the Sub-tropical climate of Australia

<table>
<thead>
<tr>
<th>Orientation</th>
<th>$C_{NW}$</th>
<th>$C_S$</th>
<th>$C_E$</th>
<th>$C_{DT}$</th>
<th>$D_{DT}$</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>3.904</td>
<td>0</td>
<td>0</td>
<td>-0.447</td>
<td>5.13</td>
<td>346</td>
</tr>
<tr>
<td>S</td>
<td>0</td>
<td>-0.021</td>
<td>2.67</td>
<td>-0.447</td>
<td>5.13</td>
<td>107</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>0.115</td>
<td>4.58</td>
<td>-0.447</td>
<td>5.13</td>
<td>185</td>
</tr>
<tr>
<td>W</td>
<td>6.299</td>
<td>0</td>
<td>0</td>
<td>-0.447</td>
<td>5.13</td>
<td>216</td>
</tr>
</tbody>
</table>

The ETTV for north and west orientation can be written as:

$$\text{ETTV}_N = C_{NW} U_N (1 - \text{WWR}) + [C_{DT} (U_f) + D_{DT} (U_d)](\text{WWR}) + S_{F_N} (\text{CF}) (\text{WWR})SC \quad (4.19)$$

$$\text{ETTV}_W = C_{NW} U_W (1 - \text{WWR}) + [C_{DT} (U_f) + D_{DT} (U_d)](\text{WWR}) + S_{F_W} (\text{CF}) (\text{WWR})SC \quad (4.20)$$

The ETTV for south and east orientation can be written as:

$$\text{ETTV}_S = [C_S (U_S) + C_E (U_E)] U_S (1 - \text{WWR}) + [C_{DT} (U_f) + D_{DT} (U_d)] \text{WWR} + S_{F_S} (\text{CF}) (\text{WWR})SC \quad (4.21)$$

$$\text{ETTV}_E = [C_S (U_S) + C_E (U_E)] U_E (1 - \text{WWR}) + [C_{DT} (U_f) + D_{DT} (U_d)] \text{WWR} + S_{F_E} (\text{CF}) (\text{WWR})SC \quad (4.22)$$

In the presence of external shading devices the formulation for north and west orientation can be written as:

$$\text{ETTV}_N = C_{NW} U_N (1 - \text{WWR}) \times E_{SCI} + [C_{DT} (U_f) + D_{DT} (U_d)](\text{WWR}) + S_{F_N} (\text{CF}) (\text{WWR})SC \times E_{SCW} \quad (4.23)$$
Similarly formulation for south and east orientation in presence of external shading devices can be written as:

\[
\text{ETTV}_s = [C_s (U_s^2) + C_E (U_E)] U_s (1 - \text{WWR}) x E_{SC1} +\left[ C_{DT} (U_f^2) + D_{DT} (U_d)\right] \text{WWR} + SF_s (CF) (\text{WWR})(SC) \times E_{SCW}
\]

(4.25)

\[
\text{ETTV}_e = [C_s (U_E^2) + C_E (U_E)] U_E (1 - \text{WWR}) x E_{SC1} +\left[ C_{DT} (U_f^2) + D_{DT} (U_d)\right] \text{WWR} + SF_e (CF) (\text{WWR})(SC) \times E_{SCW}
\]

(4.26)

**Formulation of conduction heat gain part of wall**

From equation (4.21), conduction heat gain part of south facing wall,

\[
\text{ETTV}_s = C_s (U_s^2) + C_E (U_E) U_s (1 - \text{WWR})
\]

\[
= C_s \left[ (U_s^2) + (C_E/C_s)U_s^2 \right] \times C_{WWR}
\]

\[
= C_s \left[ F (U_s) + (C_E/C_s)F (U_s) \right] \times C_{WWR}
\]

(4.27)

From equation (4.22), Conduction heat gain part of east facing wall,

\[
\text{ETTV}_e = C_s \left[ F (U_E) + (C_E/C_s)F (U_E) \right] \times C_{WWR}
\]

(4.28)
Formulation of conduction heat gain part of window

From equations (4.18 - 4.26), conduction heat gain part of window for any orientation

\[ = [C_{DT}(U_1^2) + D_{DT}(U_1)](WWR) \]

\[ = [C_{DT} \times F(U_1) + D_{DT} \times F(U_1)] \times C_{WWR} \]

\[ = C_{DT} \times [F(U_1) + (D_{DT}/C_{DT}) \times F(U_1)] \times C_{WWR} \]  

(4.29)

4.6 Discussion

4.6.1 ETTV coefficients

From the analysed result of conduction heat gain by wall and its relationship with U value of wall, it has been established that the coefficient \( C_{NW} \) is orientation dependent. The west wall has the highest conduction heat gain as peak solar gain usually occurs in the west wall during the day in a sub-tropical climate. The lowest gain has been found in the south facing wall, therefore the coefficient \( C_S \) is lowest for this orientation. The coefficient value varies based on the consideration of net heat gain, positive heat gain and combination of both.

The negative value of any orientation is a result of net heat losses of that orientation during winter months whereas other orientations showed gains in winter months. The coefficients \( C_{NW}, C_S \) and \( C_E \) have been tabulated in Table 4.11. From the analysed result of conduction heat gain by window and its relationship with U value of window, it has been established that the two coefficients \( C_{DT} \) and \( D_{DT} \) are independent of orientations and in this case, reversal of heat flow affects the conduction heat gain by window. The heat flow direction occurs more in window conduction compared to wall conduction heat gain. The value of two coefficients \( C_{DT} \) and \( D_{DT} \) are tabulated in Table 4.11. The conduction heat gain part by wall for south and east facing wall as a function of U value of wall is shown in equation (4.27) and (4.28). The conduction heat gain part of north and west facing wall can be written as U value of wall as well. The conduction heat gain part of window as a function of U value of window is shown in equation (4.29).
Solar factors have been tabulated in Table 4.11. Solar factors retrieved from analysis have a significant impact on heat gain of buildings. From the relationship between solar heat gains by window and SC of fenestration system, it is clear that a positive linear relationship is established among them. The highest solar factor has been investigated in north orientation and the second highest is in west orientation. The lowest has been observed in south orientation. Transmissibility, absorptivity and thermal transmittance value of glass also affect the determination of accurate solar factors.

4.6.2 External Shading Coefficient

External shading coefficients for wall and window are significant contributors if the external shading device is located before a certain distance from the upper side of the window. The external shading coefficient has an effect on wall area above the window, but the effect is nearly zero for the lower portion of the wall under the window. The coefficient $E_{sc}$ for different orientations is an important consideration when considering heat gain in the presence of external shading devices. For various shading angles of external shading devices, the values differ. The tabulated value shown in Table 4.9 and 4.10 can be used for heat gain calculation in the presence of this type of external shading device. However, if external shading devices are located just before the window, then only the external shading coefficient due to overhang needs to be considered for the window.

4.6.3 Validation of determined coefficient of ETTV and estimation of cooling energy

The computed ETTV value of buildings using formulation (equations 4.19-4.26) showed a positive linear relationship with annual space cooling energy consumption simulated in eQUEST for different constructions of wall and window as shown in Figure 4.22. The fenestration system of five actual case-study buildings were reflective glass and the computed value from 54 different glass constructions provided the positive heat gain relationship with annual space cooling energy consumption. The ETTV value found in these case-studied buildings was in the range 24 to 42 (W/m²). Again, if the window construction details (for example, low emissivity or double clear or tinted glass) have been changed, the ETTV value may vary as SC and transmissibility of glass have an impact on solar heat gain on window.
Finally, the cooling energy of 10 different commercial buildings has been calculated using new formulation and the determined ETTV. Figure 4.23 presents the relationship of ETTV values and annual cooling energy consumption for the 10 buildings, case studied in this research. It can be seen that a positive relationship between ETTV and annual cooling energy consumption of 10 buildings exists. The determined R value of the linear regression was 0.99 as shown in Figure 4.23. So it can be concluded that ETTV has a linear relationship with space cooling energy consumption and the estimation of cooling energy can be obtained from the ETTV application.

Figure 4. 22: Correlation between computed ETTV of buildings with annual space cooling energy consumption (325 parametric runs)

Figure 4. 23: Correlation between computed ETTV of 10 buildings with annual space cooling energy consumption
4.6.4 Comparison among calculated, actual and simulated cooling energy quantification

Conventional method of estimating space cooling energy is based on space area. ETTV value is positively and linearly related with the space cooling energy requirements. The general concept of ETTV is that the higher the ETTV value of a building, the more space cooling energy consumption by that building. The other factors, for example lighting, occupancy and other plug loads, have an impact on cooling energy consumption of buildings. However, the envelope heat gain is a major part of building heat gain and cooling energy estimation. After the computation of ETTV coefficients, the annual cooling energy consumption of 10 buildings has been calculated based on a mathematical model developed by Chua and Chou (2010a). A comparison of ETTV based estimated annual cooling energy with the actual cooling energy (collected from consultancy firms by author) and simulated value (as has been discussed in section 4.2) is presented in Figure 4.24. From Figure 4.24, it can be seen that the calculated value based on ETTV showed more accurate estimation with the actual consumption rather than the simulated results. Sometimes the simulation value may provide over cooling energy consumption estimation that may lead to design or application of oversized chillers. Therefore, ETTV-based cooling energy estimation provides more accurate cooling energy consumption of commercial building in the sub-tropical climate of Australia.

Figure 4.24: Comparison of annual cooling energy consumption
4.6.5 Comparison of ETTV-based cooling energy with that of standard software with highly insulated roof

For a heavily insulated roof, the heat gain through roof can be considered negligible compared to envelope heat gain for high rise commercial building. Usually for high rise commercial buildings, the roof area is comparatively smaller than the roof area of other type of commercial spaces like low rise commercial offices and retail stores. So the heat gain component is envelope for high rise commercial building without the heat gain by roof. A comparative study has been conducted among ETTV-based methods and other available software to identify the cooling energy requirement for high rise commercial building with highly insulated roof. The estimated cooling energy consumption of case study buildings based on ETTV has been compared with simulated cooling energy by two software Trane Trace v6.2.6.5 (used in different consultancy firms) and eQUEST v.3.64 and presented in Figure 4.25. From the Figure 4.25, it has been observed that ETTV based estimation provides lowest cooling load.

![Figure 4.25: Comparison of cooling energy estimation by ETTV and standard software](image)

However, in ETTV based calculation, cooling loads resulting from lighting and office equipment is not taken into consideration. But these loads can be considered minimum compared to building heat gain. Possible reason behind the differences between the ETTV-based method and standard software is that standard software considers weather data saved in a specific file that is not an updated one. In addition, roof heat gain and inclusion of skylight,
lighting and other plug load variation and some default values of HVAC data in cooling energy calculation provides some over-estimation in cooling energy consumption analysis. However, if all heat gains due to envelope and internal gain (e.g., ETTV plus miscellaneous load (W/m²), computed by summation of ETTV, lighting, equipment and other load (if necessary)) were included in space cooling energy estimation, then the results showed 5 to 10% deviation of actual consumption as shown in Figure 4.26 from the 10 case-studied commercial buildings. So, it can be concluded that the ETTV based energy calculation provides more accurate estimation than software and saves the amount of energy.

![Figure 4.26: Cooling energy consumption based on ETTV and actual consumption](image)

The roof heat gain needs to be considered for more accurate heat gain and cooling energy estimation for mid-rise and low rise commercial building that has been discussed in the next section.

**4.6.6 Building envelope and roof heat gain in an integrated heat gain model for quantification of cooling energy**

A roof receives significant amounts of solar radiation every year. The data available on the ASRDH handbook indicates that average global hourly solar radiation and daily radiation on horizontal surfaces is significant (ASRDH, 2006). Conduction heat gain would be high if the roof was not insulated. This can result in high air-conditioning energy consumption or high
discomfort hours if the space is not ventilated. In Australia, most commercial buildings have Galvanised and Zincalume roofing which act as poor reflectors of solar energy. So roof heat gain needs to be considered for low rise commercial buildings like office buildings, shopping malls, supermarkets etc. For uninsulated roof or less insulated roof, the heat gain needs to be considered for low-rise commercial buildings whenever the opaque roof absorbs heat from outside. In many commercial buildings, there are opaque roofs and ETTV doesn’t consider the heat gain of roof. So there is always a necessity to consider both heat gain by envelope and roof for opaque envelope and roof.

The total heat gain of building, $H_g$ (W/m²) has been calculated based on an integrated heat gain model comprised of weighted average ETTV of exterior wall area, $ETTV_0$ (combining equations 4.19-4.29 and weighted average of individual orientations) and the steady-state heat transfer process of roof as shown in equation (4.30). The required annual cooling energy consumption, $E_c$ (MWh/yr) has been calculated based on cooling load estimation model. (Chua and Chou, 2010a; Chua and Chou, 2011). The revised $E_c$ shown in equation (4.31) has been calculated based on building integrated heat gain model as shown in equation (4.30) and combination of equations (4.5), (4.19-4.26) and roof heat gain equation (Suhrcke et al., 2008). Then $E_c$ is compared with actual consumption of existing commercial building to validate the estimation.

$$H_g = ETTV_0 + U_r [(T_a - T_i) + \propto G/h_o ] \quad (4.30)$$

$$E_c = (\gamma \cdot A_{en}) \cdot H_g \cdot 24 \cdot (D) \cdot C_m / \Delta t \cdot (COP)^n \quad (4.31)$$

### 4.6.7 Cooling energy consumption ($E_c$) of commercial buildings with uninsulated roof

As discussed in the previous section, the roof heat gain is significant in the case of low or mid-rise commercial buildings. Thus, to investigate the significance of cooling energy estimation, two different analyses have been conducted, keeping the same internal heat gain in both cases. First of all, only the envelope heat gain has been considered and corresponding cooling energy consumption has been calculated for four case-studied buildings. Using the
collected data of four commercial buildings, the relationship of mathematically calculated value of envelope heat gain and annual cooling energy consumption \( (E_c) \) has been found a bit of non-linear in the sub-tropical climate zone of Australia as shown in Figure 4.27. However, if data of one case studied building is discarded, the relationship would be linear. The increment of number of data sets of number of case studied buildings may provide accurate prediction of relationship between cooling energy and heat gain.

![Figure 4.27: Cooling energy \( (E_c) \) against ETTV plus other load \( (W/m^2) \)](image)

The deviation is also present in total calculated cooling energy value when compared with the actual cooling energy consumption as shown in Figure 4.28. The reason for the deviation is because the only heat gain by the external walls and internal heat gain have been considered. Some variations of envelope parameters, occupancy schedule, operating hours and approximate value of some envelope parameters may also affect actual \( E_c \) estimation.

In the second analysis, the roof heat gain considered with envelope heat gain as an integrated heat gain model, and the analysis, has been conducted. Using the collected data of four commercial buildings, the relationship of mathematical calculated value of total heat gain \( (H_g) \) and calculated annual cooling energy consumption \( (E_c) \) has been found a bit of non-linear as well in the sub-tropical climate zone of Australia as shown in Figure 4.29. However, the correlation between cooling energy consumption and building integrated heat gain model was more accurate than the first analysis. \( R^2 \) value in the second analysis (Figure 4.29) was 0.99 whereas it was 0.94 in the first analysis (Figure 4.28). The roof heat gain consideration...
in the integrated heat gain model is significant because the estimated heat gain and cooling energy consumption provided a more accurate result as shown in Figure 4.30 rather than considering only envelope heat gain in low-rise (6-10 floors) commercial spaces such as retail and office buildings.

Figure 4. 28: Comparison of cooling energy ($E_c$) consumption (between calculated and actual when only envelope and other heat gain being considered)

Figure 4. 29: Cooling energy ($E_c$) Vs heat gain by envelope, roof and other load (W/m$^2$)
However, as the present model considers the roof heat gain, so the variation of cooling energy consumption between the calculated and actual consumption is found to be 5-6 %. The calculated annual cooling energy based on wall and roof area as considered in the integrated heat gain model, showed variations of 6-8 % with annual cooling energy calculation based on space area by eQUEST. On the other hand, annual cooling energy based on wall and roof area showed some variations with the targeted value of annual cooling energy based on the net lettable area of commercial building in Brisbane; whereas E\textsubscript{c} based on wall and roof area is far below the annual cooling energy of the existing building benchmark of Brisbane as shown in Figure 4.31. However, if the similar buildings are constructed in this region, then it showed a bit of variation with design target value of new buildings. The building no 1 and 2 showed around 0.8-1.8 % variation with design target value whereas building 3 and 4 showed around 20% and 13% respectively. It is noteworthy that the annual cooling energy is calculated based on envelope and roof area in this analysis whereas the design target is usually considered based on space area. So a correlation factor can be considered between envelope area and space area to reduce the percentage of variation. The number of more case studies can provide a more accurate result of the comparisons.
Chapter 4

4.7 ETTV application to buildings of other regions

4.7.1 Case study of commercial shopping centre in Sub-tropical Bangladesh

To investigate the Envelope Thermal Transfer Value (ETTV) on a commercial shopping centre, some shopping centres located in Dhaka, capital of Bangladesh, have been studied and ETTV value and annual cooling energy consumption have been estimated. Some of the data relevant to ETTV and air-conditioning have been added in Appendix 8. The ETTV value computed for Bashundhara City (the largest shopping centre in Bangladesh), Motaleb Plaza and Karnafuli Garden City, were 59 (W/m²), 28 (W/m²) and 23 (W/m²) respectively. The computed annual cooling energy consumption based on ETTV was nearly the same as the actual cooling energy consumption of these buildings as shown in Figure 4.32.

Figure 4. 31: Annual cooling energy (KWh/m²pa) compared with design target and benchmark (Design target and benchmark, Source: AIRAH, 2007)
4.7.2 Case study for multi-storied commercial office and administrative building in the hot humid climate of Saudi Arabia

To investigate the ETTV and multi-storied commercial office building, one multi-storied commercial building and one administrative building of the General Directorate of Military Works (GDMW) of Saudi Arabia have been studied. Details of the data of these buildings have been added in Appendix 9. The ETTV value computed for the commercial building was 22.2 (W/m²) whereas for the administrative building it was around 29 (W/m²). The results from Figure 4.33 showed that calculated annual cooling energy based on ETTV has a close relationship with the actual cooling energy consumption. However, some deviations have been observed as roof heat gain and some plug loads have been discarded during calculation.
Conclusion

The newly developed formulation of ETTV and its coefficient for commercial building has a significant contribution in improving the thermal and energy performance of commercial buildings. The coefficients and formulation of different orientations provides better understanding of the heat gain and energy consumption consideration for space cooling of commercial buildings. The coefficients determined from the study can be used to determine ETTV value and cooling energy estimation of shopping centre, residential and administrative building, as has been found from some case-studied building analysis. ETTV as a building energy code is still being studied in different climates of the world for energy efficient planning, design and climate-specific design of commercial building. Furthermore, ETTV-based cooling energy estimation provides more accurate estimation of high rise commercial building rather than commercial software in which some default values may provide over-estimation or design of oversized chillers. In addition, building heat gain models developed in this study provide more accurate estimation of cooling energy consumption of low and mid-rise commercial building where roof area is significant or un-insulated roof. The case study of the buildings in different climates also provides an idea for further evaluation and
formulation of ETTV for other climates following the procedure discussed in this chapter. This would obtain a better prediction and estimation of cooling energy for new buildings and a study of existing buildings to reduce the ETTV and to reduce the cooling energy consumption. Finally, it can be concluded that ETTV can be used for estimation of cooling energy performance and the lower ETTV value contributes the lower cooling energy consumption of buildings, which has significant influence on energy performance improvement of buildings.
Chapter 5: Investigation of Energy performance of commercial buildings by Green applications

Summary

In this chapter, mathematical modelling for heat gain and cooling energy performance using ETTV for wall and steady-state heat gain of roof has been developed. Next, the thermal transmittance value of Living wall and Green roof systems has been determined and discussed. The detailed description of the analysis of Living wall, Green roof and Green facade system for commercial buildings has been provided. The characteristics of commercial building on which heat gain and energy performance analysis has been conducted and the approach of determination of energy performance have been demonstrated. The experimental investigation of Living wall and Green roof, conducted in an experimental facility, has been depicted next. Once thermal performance of Green shed has been observed, the detailed procedures with mathematical modelling regarding thermal performance analysis of commercial building wall and roof have been demonstrated. Finally, heat gain and cooling energy performances of commercial buildings have been quantified and demonstrated in the presence of these applications (i.e., Living wall, Green facade and Green roof), using temperature data, shading coefficient value, heat gain equation made of ETTV formulation developed in Chapter 4, and steady-state heat gain of roof.

A brief overview of the analysis of Living wall, Green facade and Green roof, has been conducted for commercial building application, is given below.

Reduction of cooling energy requirements of a building leads to reduction of energy consumption of that building as has been discussed in Chapter 2. The application of Living wall, Green facade and Green roof can reduce the cooling energy consumption of a building. Like the Envelope Thermal Transfer Value (ETTV), Green applications i.e., Living wall, Green facade and Green roof technologies, can be applied in both design and operation stages of the building to improve the energy efficiency. In the present study, a relationship has been established between the heat gain equation and cooling energy consumption of commercial building in the presence of these Green applications. ETTV deals with the heat gain of the building, therefore Living wall and Green facade are closely related with the ETTV, which has been shown later on in this chapter. The heat gain equation includes ETTV for envelope and steady state roof heat gain individually and as a combination of both, depending on the
necessity of the application of Living wall, Green facade and Green roof. In this research, the heat gain effect in the presence of Living wall has been considered in west facing walls as solar energy absorbed in west facing walls during the afternoon is significant. However, the climate-specific design for these applications and their performance before application in real building is an issue that needs to be considered for obtaining a long-term thermal, energy and environmental effect for commercial buildings.

The next section will demonstrate the mathematical investigation in absence and in presence of Living wall, Green facade and Green roof technologies. Some parts of the following sections (Section 5.1 to 5.8) are presented and published by Author during candidature (Hasan et al., 2012a; Hasan et al., 2012b).

5.1 Investigation of energy performance of Living wall, Green facade and Green roof

5.1.1 Commercial building heat gain and cooling energy consumption in absence of Living wall and Green facade system

Using the fundamental equation of ETTV (Chua and Chou, 2010a), the following formulation (5.1) has been developed for west facing walls of building located in Australian sub-tropical climate in Chapter 4. The equation (5.1) will be modified later on for different Living wall, Green facade and Green roof combinations (e.g. equations 5.6, 5.11, 5.15, 5.18).

\[
\text{ETTV}_W = C_{NW} U_W (1 - \text{WWR}) + (C_{DT}(U^c_i) + D_{DT} (U_i))(\text{WWR}) + S_{W}(\text{CF})(\text{WWR})SC
\]  

The coefficient \( C_{NW} \) is linearly regressed from a huge amount of data sets and it is a predetermined value. Again, the coefficient \( C_{NW} \) is applicable on west and north-facing orientations whereas south and east orientations have different coefficients. So, the coefficient \( C_{NW} \) is equivalent to \( T_{D_{eq}} \) for the west-facing wall for a particular case (i.e., \( C_{NW} U_W (1 - \text{WWR}) \equiv T_{D_{eq}} (1 - \text{WWR}) U_w; \ C_{NW} \equiv T_{D_{eq}} \)) whereas other orientations have a different ETTV formulation as has been discussed in Chapter 4.
The total heat gain by envelope, $H_t$ as shown in equation (5.2), can be written from a weighted average value of the ETTV of all orientations

$$H_t = \frac{(\text{ETTV}_w \times A_w + \text{ETTV}_n \times A_n + \text{ETTV}_s \times A_s + \text{ETTV}_e \times A_e)}{(A_w + A_n + A_s + A_e)} \quad (5.2)$$

As per Chua and Chou’s (Chua and Chou, 2010a) mathematical model of cooling energy consumption, $E_c$ shown in equation (5.3) can be written as

$$E_c = (\gamma \times H_t \times A_e) \times 24 \times D \times (a \times b)/\Delta t \times (\text{COP})^n \quad (5.3)$$

5.1.2 Commercial building heat gain and cooling energy consumption in the presence of only Living wall system

A schematic view of Living wall system on west facing wall is shown in Figure 5.1.

![Figure 5.1: Living wall system on building wall](image)

Due to Living wall in an opaque part of a west facing wall, the equation for equivalent temperature difference would be
\[ TD_{eqg} = (T_l - T_{ai}) + [ \alpha \times R_{so} \times (I_t) ] \] (5.4)

\[ I_t \text{ will be zero for building wall due to the presence of Living wall in front of building wall, so the equation (5.4) becomes} \]

\[ TD_{eqg} = (T_l - T_{ai}) \] (5.5)

Hence, the heat gain equation for west facing wall in the presence of Living wall system using equations (5.5) and (5.1), become

\[ ETTV_{lw} = TD_{eqg} \times w_a \times (1 - WWR) + [ C_{DT} \times (U_t^2) + D_{DT} \times (U_t)(WWR) + SF \times (CF)(WWR) \times SC ] \] (5.6)

If a west facing wall is covered by Living wall and other walls remain uncovered, the weighted average heat gain and cooling energy consumption would be

\[ ETTV_b = (ETTV_{lw} \times A_w + ETTV_n \times A_n + ETTV_s \times A_s + ETTV_e \times A_e) / (A_w + A_n + A_s + A_e) \] (5.7)

and

\[ E_{cw} = (\gamma \times A_t \times (ETTV_b)) \times 24 \times D(a)(b) / \Delta t \times (COP)^n \] (5.8)

The difference between west facing wall with Living wall system and without Living wall system for a whole building envelope is the variation of equivalent temperature and U value of wall.

**5.1.3 Commercial building heat gain and cooling energy consumption in presence of only Green facade system**

A schematic view of Green facade system on west facing wall and on west facing window is shown in Figures 5.2 and 5.3 respectively.
As per Monsi and Saeki (2005) and Breda (2003) the solar radiation before the canopy and behind the canopy can be written as follows

\[
\frac{l_0}{l_t} = e^{(-K \cdot LAI)}
\]

(5.9)

As per Gao (Gao, 1996), the ratio of solar radiation before and behind the canopy can be written as

\[
E_{sc} = \frac{l_0}{l_t}
\]

(5.10)

Using equation (5.9) and (5.10), the value of \( E_{sc} \) can be determined.

When Green facade system is in front of a west facing wall, the heat gain equation for west facing orientation can be written as:

\[
ETTV_{gfr} = TD_{eq} \cdot U_{Wa} \cdot (1 - WWR) \cdot E_{sc} + \left[ C_{DT} (U_f) + D_{DT} (U_f) \right] (WWR) + SF_W (CF) (WWR) SC
\]

(5.11)

Here, \( E_{sc} \) acts as an external shading multiplier for the wall due to Green facade system in front of wall. Devgan et al. (2010) formulated the external shading multiplier which can be applied to window as well as wall, if there is any shading effect externally outside of the window or wall, such as overhang, Green facade etc.

Figure 5. 2: Green facade system in front of wall of commercial building
If the west-facing wall is covered and other walls remain uncovered, then weighted average heat gain and cooling energy consumption respectively would be

$$ETTV_{b1} = \left( ETTV_{gI} \times A_w + ETTV_n \times A_n + ETTV_s \times A_s + ETTV_e \times A_e \right) / (A_w + A_n + A_s + A_e)$$  \hspace{1cm} (5.12)

and

$$E_{cfl} = (\gamma \ast A_I (ETTV_{b1}) \ast 24 \ast D \ast (a)(b) / \Delta t \ast (COP)^n \hspace{1cm} (5.13)$$

When Green facade system is in front of a west-facing window, the basic equation (Building and Construction Authority, 2008; BCA, 2011; Nikpour et al., 2011) for the shading coefficient of a fenestration system can be written as:

$$T_{sc} = S_{C1} \ast E_{sc} \hspace{1cm} (5.14)$$

![Figure 5.3](image_url)

Figure 5. 3: (a) Green facade system in front of window (b) in front of fenestration of building

The heat gain equation for west-facing orientation becomes

$$ETTV_{gI2} = TD_{eq} U_W (1 - WWR) + \left[ C_{DT} (U_f) + D_{DT} (U_f) \right] (WWR) + SF_W (CF) (WWR) S_{C} (T_{sc}) \hspace{1cm} (5.15)$$
If Green façade is in front of west-facing fenestration and the other fenestration of other orientations remains uncovered, therefore weighted average heat gain and cooling energy consumption respectively would be

\[
\text{ETTV}_{b2} = (\text{ETTV}_{gf2} \times A_w + \text{ETTV}_n \times A_n + \text{ETTV}_s \times A_s + \text{ETTV}_e \times A_e) / (A_w + A_n + A_s + A_e)
\]  \hfill (5.16)

and

\[
E_{cf2} = (\gamma \times A_t(\text{ETTV}_{b2}) \times 24 \times D(a)(b) / \Delta t \text{(COP)})^n
\]  \hfill (5.17)

5.1.4 Building heat gain and cooling energy consumption in the presence of Living wall on opaque part of west facing wall and Green facade system on west-facing fenestration

A schematic view of both Living wall and Green facade system on west facing wall of building is shown in Figure 5.4. If Living wall on an opaque part of wall and Green facade is in front of a fenestration system, and is placed in west-facing wall, the heat gain equation can be written in the following form:

\[
\text{ETTV}_{lg} = T_{D_{	ext{avg}}} U_{wa} (1 - \text{WWR}) + [C_{\text{DT}} (U_f) + D_{\text{DT}} (U_f)](\text{WWR}) + S_{\text{f}} (\text{CF}) (\text{WWR}) SC (T_{so})
\]  \hfill (5.18)

Figure 5.4: Living wall on building wall and Green facade on window side in a combined system

If other walls remain uncovered, the weighted average heat gain and cooling energy consumption can be expressed by equations (5.19) and (5.20) respectively.
5.1.5 Combined Living wall and Green roof heat gain model

In this section, the mathematical model for heat gain by concrete roof and heat gain by concrete roof with Green roof has firstly been discussed and then the combined heat gain estimation has been demonstrated.

(a) Concrete roof model (without Green roof)

The initial model of concrete roof has been considered from the developed model of Suehrcke et al. (2008). A schematic diagram of concrete roof without Green roof is shown in Figure 5.5.

\[ E_{cb} = (\gamma \cdot A_t(ETTV_{bo}) \cdot 24 \cdot D(a)\cdot(b)/ \Delta t \cdot (COP)^n \]  

\[ ETTV_{bo} = (ETTV_{tg} \times A_w + ETTV_n \times A_n + ETTV_s \times A_s + ETTV_e \times A_e) / (A_w + A_n + A_s + A_e) \]
Chapter 5

Total heat gain by concrete roof, as per Suehrcke et al. (2008).

\[
Q_c = U_c [\Delta T_{\text{air}} + \Delta T_{\text{solar}}] = U_c [(T_a - T_i) + \alpha G/h_0]
\]

(5.21)

Where,

Total heat transfer coefficient between roof and ambient air, \( h_0 \) (W/m\(^2\)k)

\( h_0 = h_c + h_r (T_c - T_{\text{sky}})/(T_c - T_a) \) has been developed by Suehrcke et al. (2008).

\( U_c \) is the thermal conductivity of concrete roof, we can consider values from AIRAH, \( U_c = 2.2 \) W/m\(^2\)k.

\( T_c \) is the temperature of the concrete roof surface (\(^0\)C)

Radiative heat transfer coefficient between roof surface and sky, \( h_r \) (W/m\(^2\)k) used in \( h_0 \) determination can be expressed as

\[
h_r = \sigma \varepsilon (T_c^2 + T_{\text{sky}}^2) (T_c + T_{\text{sky}})
\]

(5.22)

(b) Concrete roof model with Green roof

A schematic diagram of concrete roof with Green roof is shown in Figure 5.6.

![Concrete roof with Green roof](image)

Figure 5. 6: Concrete roof with Green roof

The total heat gain by concrete roof with Green roof, \( Q_t \) would be

\[
Q_t = U_t [\Delta T_{\text{air}} + \Delta T_{\text{solar}}] = U_t [(T_a - T_i) + \alpha G/h_0]
\]

(5.23)
Here,

\( U \) is the total heat transfer coefficient of Green roof (\( U_g \)) and concrete roof (\( U_c \)), (W/m\(^2\)K)

\( U_g \) (W/m\(^2\)K) is heat transfer coefficient of Green roof and needs some analysis based on thermal resistance, which will be discussed later on in this research.

\( T_g \) is the temperature of the Green roof surface (\(^0\)C) that was measured from the set up.

Outside total heat transfer coefficient between Green roof and ambient air, \( h_{0g} \) (W/m\(^2\)K) is shown in equation (5.24).

\[
h_{0g} = h_c + h_{rg} (T_c + T_{sky}) / (T_g - T_s)
\]  

(5.24)

Radiative heat transfer coefficient between Green roof surface and sky, \( h_{rg} \) (W/m\(^2\)K) shown in equation (5.25) is

\[
h_{rg} = \sigma \cdot \varepsilon \cdot (T_g^4 + T_{sky}^4) / (T_g + T_{sky})
\]  

(5.25)

**5.1.6 Mathematical model of combined roof (Concrete roof and Green roof)**

A difference has been reported between conventional flat concrete roof and combined roof (concrete roof with Green roof) systems. The main part would be the addition of U value of Green roof and the difference of radiative heat transfer coefficient between roof surface and sky, \( h_0 \). The total U value of the combined system would be the sum of thermal resistance and the reversal of that value. The surface temperature of the Green roof and internal air temperature of space under the Green roof system also contributes the variation of radiative heat transfer coefficient value for a combined system. A summary of mathematical formulation has been shown below (Table 5.1).
### Table 5.1: Summary of Mathematical formulation of both roofs

<table>
<thead>
<tr>
<th>Concrete Roof/ Roof without Green application</th>
<th>Concrete roof with Green roof</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suehrcke et al. (2008).</td>
<td>(Modified by Author for Green applications)</td>
<td></td>
</tr>
<tr>
<td>Total heat gain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Q_c = U_c [\Delta T_{air} + \Delta T_{solar}] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>= ( U_c [ (T_a - T_i) + \alpha G/h_0] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor air temperature Ti can be measured in case of concrete roof</td>
<td>Indoor air temperature Ti can be measured for concrete roof with Green roof</td>
<td>Indoor air temperature variation can be measured from experiment</td>
</tr>
<tr>
<td>Convection heat transfer coefficient, ( h_c = \rho_a C_{pa} C_H u )</td>
<td>Convection heat transfer coefficient, ( h_c = \rho_a C_{pa} C_H u )</td>
<td>Same in both case</td>
</tr>
<tr>
<td>Radiative heat transfer coefficient between roof surface and sky</td>
<td>Radiative heat transfer coefficient between Green roof surface and sky</td>
<td>Difference in concrete roof surface temperature, ( T_c ) and Green roof surface i.e. media surface temperature, ( T_g ). Need measurement</td>
</tr>
<tr>
<td>( h_r = \sigma \varepsilon (T_c^2 + T_{sky}^2) (T_c + T_{sky}) )</td>
<td>( h_{rg} = \sigma \varepsilon (T_g^2 + T_{sky}^2) (T_g + T_{sky}) )</td>
<td></td>
</tr>
<tr>
<td>Outside total heat transfer coefficient between roof and ambient air, ( h_0 (W/m^2k) )</td>
<td>Outside total heat transfer coefficient between Green roof and ambient air, ( h_0 (W/m^2k) )</td>
<td>Difference in ( h_0 ) value in both case due to ( T_c ) and ( T_g ) temperature difference</td>
</tr>
<tr>
<td>( h_0 = h_c + h_r (T_c-T_{sky})/(T_c-T_a) )</td>
<td>( h_{0g} = h_c + h_r (T_g-T_{sky})/(T_g-T_a) )</td>
<td></td>
</tr>
</tbody>
</table>
5.1.7 Integrated heat gain and cooling energy estimation model in presence of Living wall and Green roof

A building integrated heat gain model comprised of heat gain by wall and roof has been developed and discussed in Chapter 4. In the presence of Living wall in west-facing wall and Green roof on concrete roof, the total heat gain of the building, $H_g$ (W/m$^2$) has been calculated based on an integrated heat gain model comprised of weighted average ETTV of exterior wall area and the steady-state heat transfer process of roof as shown in equation (4.30) (Chapter 4). The required annual cooling energy consumption, $E_c$ (MWh/yr) has been calculated based on the cooling load estimation model of Chua and Chou (2010a) as shown in equation (5.28) combining equation (5.26) and (5.27) whereas equation (5.27) is similar equation (4.30) with changing of $U_{rg}$ and $h_{og}$ instead of value of $U$ and $h$.

\[ \text{ETTV}_b = (\text{ETTV}_w \times A_w + \text{ETTV}_n \times A_n + \text{ETTV}_s \times A_s + \text{ETTV}_e \times A_e)/(A_w + A_n + A_s + A_e) \]  
(5.26)

\[ H_g = \text{ETTV}_b + U_{rg} [(T_n - T_i) + \alpha G/h_{og}] \]  
(5.27)

\[ E_c = (\gamma \times A_{lw}) \times H_g \times 24 \times D \times C/ \Delta t (\text{COP})^n \]  
(5.28)

5.2 Thermal transmittance value or U value of Living wall and Green roof

Thermal transmittance or heat transfer coefficient value of Living wall and Green roof is an important consideration in Living wall and Green roof heat gain and cooling energy estimation. There is a lack of authentic literature regarding the thermal conductivity value of different construction materials of Living wall and Green roof and information regarding the thermal conductivity analysis is still in its initial stage. In the present analysis, the U value of Living wall and Green roof has been determined based on construction details i.e., type of material used with thickness consideration and based on the thermal conductivity of the original material used in the construction. The total U value of Living wall has been calculated using the following equation (5.29).

\[ U_t = \frac{1}{R_t} = (1/R_c + 1/R_f) \]  
(5.29)
The thermal resistance of a concrete wall and Living wall provides the thermal transmittance of envelope of any specific orientation. The thermal transmittance of concrete roof and Green roof provides the total thermal transmittance of the combined roof system that includes the concrete roof and Green roof. The concrete wall and concrete roof construction characteristics have been considered based on the construction characteristics of commercial building as has been considered in Chapter 4.

The construction details of the concrete wall and roof of case studies building are given in Table 5.2 and 5.3. The construction details of Living wall and Green roof are given in Table 5.4 and 5.5.

Table 5.2: Construction details of Concrete wall of case study building
(Construction characteristics retrieved from available data of consultancy firm)

<table>
<thead>
<tr>
<th>Component</th>
<th>U value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>External opaque wall</td>
<td>2.2 W/m²K</td>
<td>12.5 mm ceramic tiles + 200 mm HW concrete + 100 mm airspace + 10 mm plaster board</td>
</tr>
</tbody>
</table>
Table 5. 3: R value and total U value of Living wall, $U_1$ (Construction characteristics retrieved from Elmich supplier)

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Composition</th>
<th>R value considered $(m^2K/W)$</th>
<th>Thickness in existing Living wall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Elmich Living wall module (As per supplier information)</td>
<td>5.98</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Geotextile</td>
<td>0.029</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Bioganic Earth Mix (Growing media)</td>
<td>0.095</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>Mulch</td>
<td>0.069</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Summation of Thermal Resistance, R $(m^2K/W)$</td>
<td>6.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summation of Thermal Conductivity, $U$ total $= U_1 (W/m^2K)$</td>
<td>0.16</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. 4: Construction characteristics of Concrete Flat Roof (Construction characteristics retrieved from AIRAH, 2007 p 158)

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Composition</th>
<th>R value considered $(m^2K/W)$ for down ward heat flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Outdoor air film</td>
<td>0.04</td>
</tr>
<tr>
<td>2</td>
<td>10 mm bituminous roof membrane</td>
<td>0.061</td>
</tr>
<tr>
<td>3</td>
<td>100 mm concrete slab (2400 kg/m3)</td>
<td>0.069</td>
</tr>
<tr>
<td>4</td>
<td>100 mm non-reflective air space</td>
<td>0.077</td>
</tr>
<tr>
<td>5</td>
<td>Indoor air film</td>
<td>0.17</td>
</tr>
<tr>
<td>6</td>
<td>13 mm Gypsum board</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>Summation of Thermal Resistance, R $(m^2K/W)$</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Summation of Thermal Conductivity, $U$ total $(W/m^2K)$</td>
<td>1.73</td>
</tr>
</tbody>
</table>
Table 5. 5: R value and total U value of Green Roof, $U_g$ (From Elmich and literature*)

<table>
<thead>
<tr>
<th>SI No</th>
<th>Composition</th>
<th>*R value from source</th>
<th>R value considered (m$^2$K/W)</th>
<th>Thickness in existing Green Roof (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>Polyurethane waterproof membrane (Open cell spray polyurethane foam)</td>
<td>2.8-5 per inch</td>
<td>0.63</td>
<td>25</td>
</tr>
<tr>
<td>2*</td>
<td>25 mm polystyrene panels (For H grade)</td>
<td>0.63</td>
<td>0.63</td>
<td>25</td>
</tr>
<tr>
<td>3*</td>
<td>Elmich Versicell drainage module (Material : polypropelene)</td>
<td>4.2 per inch</td>
<td>4.2</td>
<td>25</td>
</tr>
<tr>
<td>4*</td>
<td>Elmich Versidrain 25P drainage sheet (Density has been calculated 0.9 g/cm3)</td>
<td>0.52 per inch</td>
<td>0.52</td>
<td>25</td>
</tr>
<tr>
<td>5*</td>
<td>Geotextile</td>
<td>0.029</td>
<td>0.029</td>
<td>1</td>
</tr>
<tr>
<td>6*</td>
<td>Bioganic Earth Mix (Growing media)</td>
<td></td>
<td>0.095</td>
<td>150</td>
</tr>
<tr>
<td>7*</td>
<td>Mulch</td>
<td>0.46 per 300 mm</td>
<td>0.069</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Summation of Thermal Resistance, R (m$^2$K/W)</td>
<td></td>
<td>6.173</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Summation of Thermal Conductivity, $U_{total}$ (W/m$^2$K)</td>
<td></td>
<td>0.162</td>
<td></td>
</tr>
</tbody>
</table>

* R value from source
*1, *4 (R value insulation, 2011)
*2 (Foamsales innovative foam solution, 2008)
*3 (Usp plastic, 2011)
* 5 Considered as filter layer; Wong et al. (2003)
* 6 Assuming R value =0.095 for 150 mm thickness; Wong et al. (2003)
5.3 Detailed analysis of Living wall, Green facade and Green roof

5.3.1 Suitable plants for Living wall and Green roof in the sub-tropical climate

Not all plants are suitable for Living wall and Green roof application. Very limited research has been conducted regarding the plant suitability for external Living wall and extensive Green roof application on real buildings in the sub-tropical climate of Australia. Before performing data collection for this research project, the University of Queensland and Rural Industries Research and Development Corporation (RIRDC) have examined the following plant species for a year. It has been taken as an authentic record that temperature data collection for this research project would satisfy the necessary requirement for thermal and energy performance of Living wall and Green roof technologies made up of these types of Australian natives in real building application.

These plants survive in summer, winter, autumn and spring conditions. During the experimental investigation, it was observed that all plants were in good condition. Regular watering was done and photographs taken to monitor their performance. Finally after thermal performance investigation, it can be concluded that Living wall and Green roof made of these types of Australian native plants can provide a certain amount of thermal benefit and energy performance improvement of the building. These species of plant pass all of the criteria shown in Table 5.6 and have survived for around two years and are still alive.

Table 5.6: Criteria overcome by plants used for Living wall and Green roof

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure to fix the building wall and roof</td>
<td>Not too much heavy structure required</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>Not too much maintenance required, only watering was required</td>
</tr>
<tr>
<td>Climate</td>
<td>Sustainable in all climatic condition</td>
</tr>
<tr>
<td>Thermal performance</td>
<td>Investigated and performance observed</td>
</tr>
<tr>
<td>Aesthetic appeal</td>
<td>Green plants and flower blooms</td>
</tr>
</tbody>
</table>
Living wall and Green roof made of these types of Australian native plant is suitable for the sub-tropical climate of Australia and can contribute to the energy performance of building.

5.3.2 Analysis of Living wall and Green roof for commercial building application

The whole analysis for Living wall and Green roof application on commercial building involves several steps that have been shown in Figure 5.7. U values of both extensive Living wall and extensive Green roof are calculated based on available information. The temperature data of different points of the experimental facility has been selected and temperature data has been collected to provide all the relevant data in the mathematical model for the investigation of thermal performance of Living wall and Green roof. Once thermal performance has been validated, then energy performance investigation has been conducted using the modelled equation to investigate the cooling energy saving of the commercial building.

| Formulation of mathematical model, facility and plant selection, determination of U value for thermal and energy performance of both Living wall and Green roof |
| Measure temperature data for ambient, air gap, internal air, front and sub-surface of Living wall and Green roof, internal surface of control and Green shed. |
| Compare the Control shed temperature with Green shed i.e., internal surface of wall and roof, and internal air temperature |
| Thermal performance analysis in case of real building application and relationship of ambient temperature, air gap temperature and internal air temperature |
| Use temperature data for Living wall and Green roof in ETTV and heat gain formulation to calculate cooling energy consumption and savings and compare the savings in different systems |

Figure 5. 7: Procedure of analysis of Living wall and Green roof for commercial building
5.3.3 Analysis of Green facade for commercial building application

Brisbane rainforest action and information network (BRAIN), identified Virginia creeper (Parthenocissus quinquefolia) as a non-smothering species, presently used for ornamental purpose (BRAIN, 2000). Maman and Barb identified Virginia Creeper as sub-tropical and temperate climbers (Maman, 2011; Barb, 2011). Hopkins and Goodwin suggested Virginia creeper as a preferred species due to its no-damage possibility of building walls, like other climbing ivy plants (Hopkins and Goodwin, 2011). Perez et al. (2010) measured the mean shading coefficient of the plant Virginia creeper, a deciduous climbing plant that gives shading in summer and sheds off in winter, in a Green facade system in Spain. Again, the value of light extinction coefficient, K and leaf area index, LAI were absent in Gabriel’s analysis. The value of the shading coefficient of Virginia creeper in the Australian subtropical climate would not be the same due to variations in solar intensity. To predict the shading coefficient of Virginia creeper in the Australian sub-tropical climate, the value of light extinction coefficient K was considered 0.7 for Virginia creeper due to its horizontal leaves (Plants in action, UQ). David from University of Maryland, US identified that the leaf area index of Virginia creeper was the highest after 350 days of planting which was 3.5 to 5 and the lowest during early stage of growth which was 1.5-1.9 (David, 2006). In this analysis, LAI of Virginia creeper has been varied from 1.5-5 assuming that LAI will be the highest after one year of planting. Then, the predicted incident radiation behind the Virginia creeper, $I_0$ in the sub-tropical climate zone of Australia has been obtained from equation (5.9) using the annual value of total irradiance on vertical surface, $I_v$. Finally, the shading coefficient of Virginia creeper for the Australian subtropical climate has been obtained from equation (5.10) later used in equation (5.11), (5.12) and (5.13) for heat gain and cooling energy calculation of Green facade system in front of Living wall. Again, by varying the value of different shading coefficients of different glass, the total shading coefficient, $T_{sc}$ has been obtained from equation (5.14) and later used in equation (5.15), (5.16) and (5.17) for heat gain and cooling energy calculation in the presence of Green facade system in front of fenestration system.

The process involved for determining total shading coefficient and energy performance investigation in the presence of Green facade system is shown in Figure 5.8.
Chapter 5

Determination of light extinction coefficient for specific plant, \( K \) value of from available literature

Determination of leaf area index, LAI for specific plant from plantation to final growth

Use mathematical model to calculate solar radiation behind the canopy of the plant, \( I_0 = I_t (e^{-K \times LAI}) \) and use of total solar irradiation data for west-facing orientation

Use mathematical model to calculate shading coefficient of the specific plant for the subtropical climate, \( E_{sc} = I_0 / I_t \)

Use mathematical model to calculate total shading coefficient in presence of Green facade system for the subtropical climate, \( T_{sc} = E_{sc} \times SC \)

Use of total shading coefficient \( E_{sc} \) for west-facing wall as an external shading coefficient and use of \( T_{sc} \) value for west-facing window as a total shading coefficient for glass and plant in the ETTV formulation or heat gain formulation to calculate heat gain and cooling energy consumption estimation individually or combined i.e., with Living wall or Green roof for commercial building application

Figure 5. 8: Procedure of analysis for Green facade for commercial building application

The next section will discuss how all the temperature data of Living wall, Green roof and shading coefficient value of the Green facade system has been accumulated in real building application.

**5.3.4 Living wall, Green roof and Green facade technologies on real building application**

In the sub-tropical climate of Australia, Living wall, Green roof and Green facade application on real building is still in its initial stages as a very small number of applications have been found on real commercial building applications. As discussed in the literature review chapter, most of the external Living wall and extensive Green roof applications were in temperate climate zones, and most of them are in their experimental stage (Chapter 2).
The issue is that before applying these systems, it is really important to investigate thermal performance, which can be obtained by experimental data collection and analysis during different seasons so that seasonal variation can be observed and consequently thermal performance can be established. Once thermal performance has been established by using the temperature data, cooling energy consumption of building after application of these systems can be predicted. Again, it would not be feasible to apply Living wall and Green facade technologies directly on the building before investigation of all thermal and energy analysis for a specific climate. Due to the unavailability of Living wall, Green roof and Green facade application on commercial building and the opportunity to collect data in real building application also being unavailable, the experimental studies of Living wall and Green roof have been conducted for the collection of data and later on, computation of energy performance has been investigated. The mathematical investigation has been conducted for the Green facade system using the solar radiation data, shading coefficient value and leaf area index of the plant due to an unavailability of Green facade system even in an experimental setup in the sub-tropical zone of Australia. To investigate thermal and energy performance of these systems, four commercial buildings have been studied. The details of building characteristics and air-conditioned data have been provided in Chapter 4. Some of the data relevant to buildings’ physical characteristics are given in Table 5.7. The ETTV value of these buildings has been calculated using the coefficient determined from Chapter 4. Heat gain of roof also has been calculated using the authentic modelled equation before the Green roof application. Then, using the temperature data and shading coefficient value of different Green systems i.e. Living wall, Green roof and Green facade system, the final predicted cooling energy consumption and annual energy saving has been computed by the mathematical model which has been modified and developed as per requirements of different types of application. Overall, the cooling energy saving before and after Green technologies application has been investigated for commercial buildings in the sub-tropical climate of Australia. The Table 5.8 showed the approach has been taken for analysis and computation of cooling energy saving of commercial buildings using different Green applications.
Table 5.7: Characteristics of the case studied building

<table>
<thead>
<tr>
<th>Building No</th>
<th>Number of Storey</th>
<th>Total floor area (m²)</th>
<th>Envelope Area (m²)</th>
<th>WWR</th>
<th>ETTV (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>21330</td>
<td>6195</td>
<td>0.38</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>27270</td>
<td>7005</td>
<td>0.46</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>20170</td>
<td>5389</td>
<td>0.31</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>19230</td>
<td>5262</td>
<td>0.28</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 5.8 Different types of Green application and the approach for quantification of heat gain and energy performance

<table>
<thead>
<tr>
<th>Green technologies application</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living wall application on west-facing wall of commercial building</td>
<td>Experimental investigation and then mathematical model for cooling energy consumption analysis</td>
</tr>
<tr>
<td>Green facade application on west-facing wall only of commercial building</td>
<td>Mathematical investigation using the solar radiation data, leaf area index, shading coefficient and then mathematical modelling for cooling energy consumption analysis</td>
</tr>
<tr>
<td>Green facade application on west-facing window of commercial building</td>
<td>Mathematical investigation using the solar radiation data, leaf area index, shading coefficient and then mathematical modelling for cooling energy consumption analysis</td>
</tr>
<tr>
<td>Living wall on west-facing wall and Green facade on west-facing window in a combined system</td>
<td>Experimental investigation for west-facing wall and mathematical investigation of west-facing window, then combined mathematical modelling for cooling energy consumption analysis</td>
</tr>
<tr>
<td>Living wall on west-facing wall and Green roof application on roof</td>
<td>Experimental investigation for west-facing wall and roof, then combined mathematical modelling as an integrated heat gain model for cooling energy consumption analysis</td>
</tr>
</tbody>
</table>
5.4 Experimental Investigation of Living wall and Green roof

The experimental investigation has been conducted in an experimental facility located at the University of Queensland, Gatton. Thermal performance investigation is the first step of Living wall and Green roof’s thermal performance evaluation. To investigate thermal performance of Living wall and Green roof, the steel structure with Living wall and Green roof combination and the steel structure without any Green technologies application have been investigated during the spring time (October- November 2011) and summer time (December 2011-March 2012).

5.4.1 Experimental setup

The full picture of the two sheds, one being a control shed made of a steel structure and the other one being a Green shed made up of a steel structure with Living wall and Green roof, has been shown in Figure 3.5 (Chapter 3). As has been discussed in the previous methodology chapter, both the external Living wall and extensive Green roof system have been installed and plant suitability has been checked for one year during the winter, spring, autumn and summer time before the experimental investigation for thermal and energy performance of these technologies for this present research has been undertaken. Plants used for the living wall in the setup were Plectranthus argentatus, Plectranthus parviflorus and Bulbine vagans, whereas plants used for the Green roof in the setup were Calandrinia balonensis, Myoporum parvifolium and Sedum sexangulare.

5.4.2 Data point and Instrumentation

A schematic diagram of the data points of the setup has been shown in Figure 5.9. Pictures of the some of the data points of the setup are shown in Figures 5.10, 5.11, 5.12, 5.13, 5.14, 5.15, 5.16, 5.17 and 5.18; which have been taken during the experimental investigation.
Figure 5. 9: A schematic diagram with data point of the experimental facility

Figure 5. 10: Some of the data logger connections with sensor point
Figure 5. 11: Internal air temperature measurement of the Green shed

Figure 5. 12: Living wall front, air gap and sub-surface* temperature measurement
(* not shown)
Figure 5.13: Green roof internal steel wall and north facing steel wall temperature

Figure 5.14: East facing and south facing wall temperature measurement
Figure 5. 15: Temperature measurement of internal steel wall (Living wall end)

West facing wall on Living wall temperature side by Type K Magnet probe 3M FG/SS lead fitted with YC 747UD data logger

West facing wall on Living wall temperature side by Thermister Probe with Tiny Tag Plus 2

Figure 5. 16: Temperature measurement of Green roof surface

Data logger covered by polythene

Green roof top surface temperature measured within 10 mm from the top placing the sensor horizontally with roof

(Sub-surface is not shown here)
The following data points have been selected for thermal and energy performance investigation of external Living wall and Green roof system. Ambient temperature has been recorded by a special type of temperature and humidity measurement sensor attached with Tiny Tag Plus 2 data loggers under a Stevenson screen near the experimental facility. The data points and measuring tools are given below in Table 5.9. The data points of the air gap temperature, Living wall front surface temperature, ambient air temperature, Green roof top surface, internal air temperature, west facing steel wall of Living wall, internal surface of steel roof under Green roof temperature are considered critical points, as data of these points are used extensively for energy performance investigation of Living wall and Green roof. Data of these points have been collected by both thermometer probe and thermister probe with different types of data logger for accurate measurement of the data point and a
comparison has been investigated if the data provides some deviations in measurement. There are 15 data points that have been identified initially and the data has been collected for these points for a specific time during the summer and spring time. The detailed collection procedure, sorting and storing of data has been described briefly in Figure 5.19.

Table 5.9: Data point, location and measuring tools of the experimental facility

<table>
<thead>
<tr>
<th>Sl No</th>
<th>Data point</th>
<th>Location</th>
<th>Measuring tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ambient temperature</td>
<td>Very near the experimental facility, west facing wall direction</td>
<td>Sensor under Stevenson screen</td>
</tr>
<tr>
<td>2</td>
<td>Living wall front surface temperature</td>
<td>Front surface of the Living wall aligned horizontally with Living wall around 10 mm from the top surface</td>
<td>Thermometer probe with YC747UD data logger</td>
</tr>
<tr>
<td>3</td>
<td>Living wall sub-surface temperature</td>
<td>Sub-surface of the Living wall aligned horizontally with Living wall around 10 mm from the bottom surface</td>
<td>Thermometer probe with YC747UD data logger</td>
</tr>
<tr>
<td>4</td>
<td>Air gap temperature</td>
<td>Between the Living wall and steel wall of Green shed</td>
<td>Thermometer probe with YC747UD data logger</td>
</tr>
<tr>
<td>5</td>
<td>Internal steel wall surface temperature for the Green shed</td>
<td>Internal wall surface of the steel wall of the Green shed</td>
<td>Type K Magnet probe 3M FG/SS lead fitted with YC 747UD and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Thermometer probe with YC747UD data logger</td>
</tr>
<tr>
<td>6</td>
<td>Internal steel roof surface temperature for the Green shed</td>
<td>Internal roof surface of the steel wall of the Green shed</td>
<td>Type K Magnet probe 3M FG/SS lead fitted with YC 747UD And</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Thermister Probe with Tiny Tag Plus 2 data logger</td>
</tr>
<tr>
<td>7</td>
<td>Internal air temperature of the Green shed</td>
<td>At the middle of Green shed, the sensor placed in air</td>
<td>Thermister Probe with Tiny Tag Plus 2 data logger</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>And</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Thermometer probe with YC747UD data logger</td>
</tr>
<tr>
<td>8</td>
<td>North facing steel wall</td>
<td>Internal wall of north end of Green shed; middle position</td>
<td>Thermister Probe with Tiny Tag Plus 2 data logger</td>
</tr>
<tr>
<td>9</td>
<td>South facing steel wall</td>
<td>Internal wall of south end of Green shed; middle position</td>
<td>Thermister Probe with Tiny Tag Plus 2 data logger</td>
</tr>
<tr>
<td>10</td>
<td>East facing steel wall</td>
<td>Internal wall of east end of Green shed; middle position</td>
<td>Thermister Probe with Tiny Tag Plus 2 data logger</td>
</tr>
<tr>
<td>11</td>
<td>Green roof front</td>
<td>Front surface of the Green roof</td>
<td>Thermister Probe with Tiny Tag Plus 2 data logger</td>
</tr>
<tr>
<td>Number</td>
<td>Location Description</td>
<td>Measurement Equipment</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Green roof sub-surface aligned horizontally with Green roof around 10 mm from the top surface</td>
<td>Thermister Probe with Tiny Tag Plus 2 data logger</td>
<td></td>
</tr>
<tr>
<td>13, 14, 15</td>
<td>West steel wall, steel roof and room temperature Control shed</td>
<td>3 separate Thermister Probe with Tiny Tag Plus 2 data loggers</td>
<td></td>
</tr>
</tbody>
</table>

**Temperature data collection and sorting procedure**

Fix the measuring tools with data loggers in the specific location of the Living wall and green roof experimental setup and set the timer for 30 minutes interval for all the measuring tools at a specific time.

Turn the timer on for all the points and then make sure collection of data has started. The data collection would be continuous for 24 hours at an interval of 30 minutes.

Check every week for the recorded data and check the battery condition as the loggers perform better if the battery condition is okay.

Download the data for every week in the computer, modify and convert data in Excel spreadsheet.

Observed all the collected data for every half an hour at a specified time set during timer on in the excel spreadsheet. Day time data has been separated and the peak temperature data for a specific time has been sorted. Peak ambient temperature data has been sorted first in this way.

Observed the peak temperature of other points corresponding to that time and peak temperature of the ambient temperature. If other peak points are not observed, then this point has been considered the peak point for that location, otherwise consider the highest temperature point of that location.

Figure 5. 19: Temperature data collection and sorting procedure
5.4.3 Reason for considering Living wall placed in west-facing wall

Living wall can be placed in any orientation of the building wall. However, before applying it on the real building, it needs to be investigated which orientation of the building has the significant contribution of total heat gain. To identify this, the temperature of the control shed structure has been examined and the temperature effect has been observed for north, south, east and west orientations. The temperature data has been recorded on the internal surface of the control shed for north, south, east and west orientations. The internal surface measuring point has been indicated in Figure 5.20.

![Figure 5.20: Point location of temperature measurement of Control shed](image)

Figure 5.20: Point location of temperature measurement of Control shed
(On structure for different orientations)

Data has been recorded every 30 minutes to check the temperature variation of the control shed and it was identified that the highest temperature effect was observed on the west facing wall compared to north, south and east facing orientations. Figure 5.21 shows that the afternoon sun is a significant contributor of heat gain of the control shed, so the building’s heat gain would be higher in west-facing walls due to the afternoon effect of scorching sun.
Figure 5. 21: Temperature variation on different orientations

(14 Oct- 17 Nov 2011)

From all the temperature data recorded in data loggers, the peak temperature of different orientations during the day time has been plotted against the number of the days. It has been depicted from Figure 5.21 that the temperature of west-facing wall is higher than any other orientations. Next section will discuss the thermal performance investigation of the control shed and Green shed.

5.4.4 Thermal performance investigation of Control shed and Green shed

As discussed earlier in this chapter, investigation of thermal performance of Living wall and Green roof in Green shed and comparison of it with control shed (having no Green technologies) needed to be investigated first to proceed to the next stage of energy performance evaluation of Living wall and Green roof in real building application. To perform the investigation of thermal performance between the two sheds, the following comparisons have been conducted. These are given below.

(a) Accurate ambient temperature measurement near the setup
(b) Internal surface temperature of west-facing wall of control shed and Green shed
(c) Internal roof surface temperature of control shed and Green shed
(d) Internal air temperature of control shed and Green shed
The temperature data of the front and sub-surface of Living wall and Green roof have been observed to investigate the temperature reduction. Now the question arises, which temperature value has been considered for all of the analysis? In this case, peak temperature value has been considered. A snapshot of the 24 hour data of three consecutive days of one measuring point of internal wall temperature of the control shed and one measuring point of the internal wall temperature of the Green shed have been presented in Figure 5.22 and Figure 5.23. During the night, the temperature values in both cases were low and it was noted that the temperature increases from 5:00 am and starts decreasing at around 5 pm as shown in Figures 5.22 and 5.23.

![Figure 5.22: Internal wall temperature observation of control shed](image_url)

(For 24 hours with 30 minutes interval)
5.4.5 Ambient temperature investigation during the experimental data collection

The ambient temperature measurement was one of the important parts of temperature data collection of the experimental setup made of Living wall and Green roof. In the thermal and energy performance analysis, the ambient temperature measured has been measured by Stevenson screen near the experimental setup during the summer and spring times. It can be noted here that ambient temperature recorded at experimental site showed some variations with the available data measured by the meteorological station located 1 kilometre from the setup. Therefore, it was necessary to collect ambient data at the site rather than using BOM data and BOM data may not be the same as the data for the site.

5.4.6 Internal surface temperature of steel wall during spring and summer time

Internal surface temperature of the steel wall of the control shed is higher than the internal surface temperature of the steel wall of the Green shed. Here, steel wall temperature of the Green shed is less, due to Living wall. The temperature variation was within the range 15-20°C in most of the days in spring from 14 October 2011 to 17 November 2011 as shown in Figure 5.24. The temperature variation was within the range 8-10°C in most of the days in spring from 14 October 2011 to 17 November 2011 as shown in Figure 5.24.
summer from 16 February 2012 to 09 March 2012 as shown in Figure 5.25. The peak temperature observed between 9 am - 4 pm has been considered in both cases.

Figure 5.24: Peak temperature variation of west facing wall of control shed and Green shed
(14 Oct - 17 Nov 2011)

Figure 5.25: Peak temperature variation of west facing wall of control shed and Green shed
(16 Feb- 09 March 2012)
5.4.7 Internal surface temperature of steel roof during spring and summer time

During the experimental data collection, it has been observed that internal surface temperature of the steel roof of the control shed is higher than internal surface temperature of the steel roof of the Green shed. Due to Green roof on the steel roof of the Green shed, internal surface temperature of the steel roof under Green roof of Green shed was less than the control shed. The temperature variation was within the range 8-25 °C during spring between 14 October and 17 November 2011, as shown in Figure 5.26. However, the temperature variation was more than 20°C on most of the days. During summer between 16 February 2012 and 09 March 2012, the temperature variation was 7-26 °C as shown in Figure 5.27. However, the temperature variation was more than 20°C on most of the days during summer, like spring.

![Figure 5.26: Peak temperature variation of internal surface of steel roof of control shed and Green shed (16 Nov - 30 Nov 2011)](image-url)
5.4.8 Internal air temperature during spring and summer time

During the experimental data collection, it has been observed that internal air temperature of the control shed is higher than internal air temperature of the Green shed. Due to Living wall in west-facing wall and Green roof on the steel roof of the Green shed, internal air temperature of the Green shed was less than the control shed. The temperature variation was within the range 7-10°C on most of the days during spring between 14 October and 17 November 2011 as shown in Figure 5.28. Temperature variation was within the range 4-10°C during summer between 16 February 2012 and 09 March 2012 as shown in Figure 5.29. During summer, some days showed the variation of temperature was around 3-4°C. The reason behind the small variation would be the rainfall effect, wind flow effect and possibly a storm or a sensor error. Around 8-10°C variation was observed in 17 days out of 23 days of data collection during summer.
5.4.9 Living wall and Green roof front surface and sub-surface temperature investigation

(a) Living wall front and sub-surface temperature investigation

It has been observed that the front surface temperature of Living wall is higher than the sub-surface temperature of Living wall. The temperature variation was within the range 0.5-3.8
°C during spring between 14 October and 17 November 2011 as shown in Figure 5.30. However, the temperature variation was more than 1.6°C on most of the days. During summer between 16 February 2012 and 09 March 2012, the temperature variation was 1.6-3.5 °C as shown in Figure 5.31. However, the temperature variation was more than 2°C on most of the days during summer between 16 February 2012 and 09 March 2012.

Figure 5.30: Peak temperature variation of front surface and sub-surface of Living wall of Green shed (14 Oct-17 Nov 2011)

Figure 5.31: Peak temperature variation of front and sub-surface of Living wall of Green shed (16 Feb 2012-09 March 2012)
(b) Green roof top and sub-surface temperature investigation

The temperature variation between front surface and sub-surface temperatures of Green roof was within the range 2.2-2.8 °C during spring between 14 October and 17 November 2011 as shown in Figure 5.32. However, the temperature variation was more likely consistent in most of the days except one day during spring between 14 October and 17 November 2011. During summer between 16 February 2012 and 09 March 2012, the temperature variation was 1.9-3.2 °C as shown in Figure 5.33. However, the temperature variation was more than 2.4°C on most of the days during summer between 16 February 2012 and 09 March 2012.

Figure 5. 32: Peak temperature variation of front and sub-surface of Green roof of Green shed
(16 Nov- 30 Nov 2011)
The procedure followed to perform a thermal performance analysis of a real building wall in the presence of Living wall system has been described here. The same procedure has been followed for the roof of real building in the presence of Green roof application. The first step of the procedure was to prepare the model for internal surface temperature (equation 5.30 and 5.31) of a steel wall in the presence of Living wall system in Green shed conditions. The second step was to compare the modelling results with the actual internal surface temperature in the presence of Living wall system in the Green shed. Once the modelled temperature showed almost same with actual temperature measurement, then a similar model was developed for walls in real building application. The predicted internal surface temperature can be determined using linear regression related to the ambient temperature condition.
Finally, the predicted internal surface temperature of a concrete wall in the presence of Living wall system (equation 5.33) has been compared with the internal surface temperature of the concrete wall without Living wall system, which has been measured by infrared sensor during the afternoon when the scorching sun has had huge impact on the heat gain of the building wall. The brief procedure for thermal performance analysis for Living wall and Green roof is shown above in Figure 5.34.

5.5.1 Mathematical model for internal surface temperature measurement

To determine the internal surface temperature of the west-facing steel wall of the Green shed, a mathematical model has been developed, and internal surface temperature has been calculated and compared with the measured internal surface temperature measured by a sensor with data logger. The analysis has been done considering the Living wall placed
around 50-100 mm distance from the building wall, like the experimental Living wall that has been placed around 50 mm from the steel wall of the Green shed. A schematic diagram has been shown in Figure 5.35 to visualize the mathematical modelling.

Using the basic concept of heat transfer (Incropera, 2004; Holman, 2002), Heat balance equation can be written as:

Heat gain by west facing wall = Heat loss by west wall to the internal air of room

\[ h \times (T_x - T_{sgo}) + U_g \times (T_{sgo} - T_{sli}) + U_a \times (T_i - T_{sli}) + h \times (T_g - T_{so}) + U_a \times (T_{so} - T_{si}) \]

\[ = h \times (T_{si} - T_r) \] (5.30)

As thickness of steel is 1 mm, so we consider \( T_{so} = T_{si} \) The model becomes for steel wall

\[ h \times (T_x \cdot T_{sgo}) + U_g \times (T_{sgo} - T_{sli}) + U_a \times (T_i - T_{sli}) + h \times (T_{li} - T_{si}) = h \times (T_{si} - T_r) \]

\[ T_{si} = \left[ h \times (T_x - T_{sgo}) + U_g \times (T_{sgo} - T_{sli}) + U_a \times (T_i - T_{sli}) + h \times T_i + h \times T_r \right] / 2h \] (5.31)

This \( T_{si} \) (°C) is modelled and noted as modelled \( T_M \) (°C) whereas measured internal surface temperature data is noted as \( T_A \) (°C)

\[ \% \text{ Error between measured and modelled data} = \left( \frac{T_A - T_M}{T_M} \right) \times 100\% \] (5.32)
In the case of the concrete wall of 100 mm thickness, $T_{sc0} \neq T_{sci}$, and assuming $T_1 = T_{sc0}$ as air gap is 50 mm and concrete wall gains heat slowly from air gap.

The model for concrete wall becomes:

$$
T_{sci} = \frac{h (T_\alpha - T_{sg0}) + U_1 (T_{sg0} - T_{sg}) + U_a (T_1 - T_{sg0}) + U_c (T_{sc0} - T_{sci})}{(U_c + h)}
$$

(5.33)

To determine the internal surface temperature of the steel roof under the Green roof of Green shed, a mathematical model has also been developed, and internal surface temperature has been calculated using equation (5.34) and compared with the measured internal surface temperature measured by a sensor with data logger. Later, the predicted internal surface temperature of concrete roof under Green roof has been calculated by equation (5.35). The analysis has been done considering the Green roof placed on the building roof. A schematic diagram has been shown in Figure 5.36 and 5.37 to visualize the systems modelled.

Modelled internal surface temperature of steel roof

$$
T_{sri} = \frac{h (T_\alpha - T_g) + U_1 T_g + h x T_r}{(U_t + h)}
$$

(5.34)
Again the percentage error is calculated using equation (5.32). Here $U_t$ is total $U$ value of steel and Green roof.

![Diagram of thermal system](image)

Figure 5.37: Green roof on concrete roof

Predicted internal surface temperature of concrete roof

$$T_{ci} = [h \times (T_e - T_g) + U_t \times T_g + h \times T_r] / (U_t + h) \quad (5.35)$$

Here $U_t$ is total value of $U$ of concrete and Green roof.

### 5.5.2 Internal surface temperature of building wall with Living wall system during spring (14 Oct - 17 Nov 2011)

Internal surface temperature of the steel wall was always lower than the steel wall without Living wall system as shown in Figure 5.38. Both modelled and actual temperatures have been plotted against ambient temperature and a linear regression relationship has been obtained. It has been demonstrated from linear regression in experimental data analysis that the actual internal surface temperature of the steel wall was more likely similar with the modelled internal surface temperature of the steel wall. The percentage of error was calculated using equation (5.32) and it was between 2 to 15 % during the measurement as shown in Figure 5.39. The predicted concrete wall temperature has been computed based on mathematical modelling similar to the steel wall as it was validated by actual internal surface...
temperature measurement and comparison with concrete wall surface temperature in the absence of Living wall system, as measured by infrared sensor. From the linear regression in Figure 5.40, it can be concluded that around 2.3 to 3.8 °C temperature reduction can be obtained in the internal surface temperature of the concrete wall with Living wall system compared to a concrete wall without Living wall system.

![Figure 5.38](image1.png)

**Figure 5.38:** Peak temperature variation of internal surface of steel wall in presence of Living wall (14 October 2011 - 17 November 2011)

![Figure 5.39](image2.png)

**Figure 5.39:** Modelled and actual temperature of steel wall in the presence of Living wall shown in Error bar (14 Oct 2011 - 17 Nov 2011)
Figure 5.40: Peak temperature variation of internal surface of concrete wall in the presence of Living wall

5.5.3 Internal surface temperature of building wall with Living wall system during summer

It has been demonstrated from linear regression of the Figure 5.41 that internal surface temperature of the steel wall was more likely similar with the modelled internal surface temperature of the steel wall corresponding to ambient condition.

Figure 5.41: Peak temperature variation of internal surface of steel wall in presence of Living wall
The percentage of error was between 2 to 10 % during the measurement. From the linear regression in Figure 5.42, it can be concluded that around 2 to 7.8 \(^{\circ}\)C temperature reduction can be obtained in the internal surface temperature of a concrete wall with Living wall system compared to a concrete wall without Living wall system as shown in Figure 5.43. On an average, 4.2 \(^{\circ}\)C temperature of internal surface can be obtained during summer time.

![Figure 5.42: Percentage error between modelled and actual temperature of steel wall in presence of Living wall](image)

![Figure 5.43: Peak temperature variation of internal surface of concrete wall in the presence of Living wall (16 Feb 2012- 09 March 2012)](image)
5.5.4 Internal surface temperature of building roof under Green roof system during spring

It has been demonstrated from linear regression of the Figure 5.44 that internal surface temperature of the steel roof was more likely similar with the modelled internal surface temperature of a steel roof corresponding to ambient condition. The percentage of error was less than 10 % in most of the days during the measurement as shown in Figure 5.45. From the linear regression in Figure 5.46, it can be concluded that around 3.6 to 7.7 °C temperature reduction can be obtained in the internal surface temperature of a concrete roof with Green roof system compared to a concrete roof without Living wall system. On an average, 5.6 °C temperature of the internal surface of a concrete roof can be obtained during spring time.

Figure 5. 44: Peak temperature variation of internal surface of steel roof in the presence of Green roof (16 Nov- 30 Nov 2011)
Figure 5.45: Modelled and Actual internal surface temperature of steel roof in the presence of Green roof shown in Error bar

Figure 5.46: Peak temperature variation of internal surface of concrete roof in the presence of Green roof (16 Nov - 30 Nov 2011)
5.5.5 Internal surface temperature of building roof under Green roof system during summer (16 Feb-09 March 2012)

It has been demonstrated from linear regression of the Figure 5.37 that the internal surface temperature of steel roof was more likely similar with the modelled internal surface temperature of a steel roof corresponding to ambient condition. The percentage of error was less than 15 % in most of the days during the measurement as shown in Figure 5.48. From the linear regression in Figure 5.49, it can be concluded that around 8 to 12 °C temperature reduction can be obtained in internal surface temperature of a concrete roof with Green roof system compared to a concrete roof without Green roof system. On an average, 10 °C temperature of internal surface of a concrete roof can be obtained during summer time.

![Graph showing temperature variation](image-url)

**Figure 5.47**: Peak temperature variation of internal surface of steel roof in the presence of Green roof (16 Feb-09 March 2012)
Figure 5.48: Modelled and Actual internal surface temperature of steel roof with Green roof system (16 Feb 2012-09 March 2012) (shown in Error bar)

Figure 5.49: Peak temperature variation of internal surface of concrete roof in presence of Green roof (16 Feb 2012-09 March 2012)

5.5.6 Reason behind percentage error

From section 5.5.2 to 5.5.5, it is demonstrated that the percentage error varies 2-15% in two cases. The percentage was in the range 2-10% in other two cases. The reason behind the variation is the effect of wind, steel wall and open field experimental setup. The percentage error can be reduced if the other orientations e.g., North, South and East wall are insulated.
The modelling and analysis is conducted for west wall. Temperature of other walls affects west wall. All walls and roof are connected by steel. In addition, some parts of the roof are uncovered. The experimental setup is made of steel which is a very good conductor and thermal resistance is nearly zero which affects the measured temperature. The affect of wind and rainfall have an impact on temperature measurement during data collection. Overall all of the above reasons, the results showed deviations. Most of the data are under 10% error except few data which showed more than 10%. However, huge amount of data set has been taken in 1/2 hr interval and the results are unique.

5.6 Relationship of air gap, internal air temperature and ambient temperature

From Figure 5.50, it has been established from the linear regression data that around 4.4 °C temperature reduction of air gap can be obtained during spring for an ambient condition. Again, it has been established from the linear regression data that around 2.4 to 4.2 °C temperature reduction of air gap can be obtained during summer months, compared to an ambient condition. The air gap temperature of the Living wall system acts as an ambient condition change due to Living wall system before the concrete wall of the building. So it has a significant impact on cooling energy consumption reduction that will be discussed in the next section of this work. The internal air temperature of Green shed for a specific ambient condition has been related from linear regression as shown in Figure 5.50 and in Figure 5.51.
Figure 5.50: Air gap temperature, internal air temperature and ambient temperature relationship (14 Oct- 17 Nov 2011)

As the experimental setup has the Living wall system on west-facing wall and Green roof system on top of the roof and other side remains steel wall, so temperatures of the other walls have an effect on internal air temperature. However, the Green shed internal air temperature obtained from linear regression was 18.4 °C to 31.7 °C for different ambient conditions as shown in Figure 5.52. On an average, internal air temperature was 24 °C during spring. On the other hand, the Green shed internal air temperature obtained from linear regression was 14 °C to 26.4 °C for different ambient conditions as shown in Figure 5.53. On an average, internal air temperature was 21.1 °C during summer. Internal air temperature of the Green shed provides the idea of internal air cooling of the building system. In general, 21-24 °C has been considered for the design of indoor air temperature of a building. For the next cooling energy consumption analysis, these temperature data have been considered for cooling energy performance of commercial buildings.
5.7 Quantification of Energy performance

Air-conditioning designers sometimes use the thumb rule for the initial estimation for the design space cooling load in different countries, as has been studied during the data collection process of this research study. They considered the cooling capacity for a particular area during the design stage of cooling. For example, a one Ton capacity chiller can be considered for the sub-tropical climate of Australia to cover a space cooling area of 480 ft$^2$; on the other hand, in a hot, humid country like Bangladesh, designers consider a one-ton capacity chiller to cover a space cooling area of 200 ft$^2$. In the case of more hot and humid environments compared to less hot and humid climates, less space cooling area is usually considered for the same capacity of chiller. So, temperature and humidity are the factors that affect capacity considered for a specific area, which leads to the design space cooling load. The correlation factor $\gamma$, used in the total annual cooling energy consumption (Section 5.1) depends on design space cooling load. The correlation factor also depends on $(ETTV_0)^* A$.

Correlation factor shown in equation (5.35) for average space cooling load, $\gamma$ can be written as:

$$\gamma = \frac{\text{(Design space cooling load)}}{((ETTV_0)^* A)}$$  \hspace{1cm} (5.35)
Design space cooling load = ((Floor area)/ specific area) * capacity considered for specific area

These two variables are always changeable for a specific design space cooling energy consumption. Again, γ and ETTV have a positive relationship with annual space cooling energy consumption as has been modelled in section 5.1. The ambient temperature, wall temperature and indoor air temperature affect equivalent temperature of the Living wall, as has been shown in section 5.1. So, the ETTV value reduces for the wall on which the Living wall is placed, and it affects the total ETTV made of all wall, and weighted average ETTV of all wall as well.

The most important matters that usually considered by designers are the ambient, indoor and internal surface temperatures. For an example, the outdoor ambient temperature is considered $30^\circ C$ for a building without Living wall system. Then if Living wall is placed in the west-facing wall of the building, the changing ambient condition for the building wall would be air gap temperature due to Living wall. The reduction of ambient air temperature leads to reduction of difference between outdoor and indoor air, and between existing indoor and designed indoor air temperature. Then, for a designed building for $30^\circ C$ outdoor and $21^\circ C$ indoor, the capacity usually considered one ton which is equivalent to 2.2 KW, whereas for a designed building or existing building, if the Living wall is placed on a west-facing wall, then a linear interpolation with ambient temperature can be conducted to set up designed cooling capacity for the same floor area. So, $30^\circ C$ outdoor ambient leads to $25.6-26^\circ C$ air gap temperature obtained from the linear regression of the previous section. This leads to 0.85 ton cooling requirement instead of one ton cooling requirement for the same floor area, due to change of ambient air temperature and reduced indoor air temperature. One point is noteworthy that indoor air temperature in the absence of Living wall in a building is usually 2-3$^\circ C$ less, whereas the indoor air temperature due to Living wall system leads to 5.7-9.3 $^\circ C$ reduction of indoor air compared to outdoor air. A greater amount of cooling energy is usually spent by chillers to cover the temperature difference ($28-21) =7^\circ C$ for an indoor design condition $21^\circ C$ with existing indoor temperature $28^\circ C$, whereas a lesser amount of cooling energy is usually spent to cover the temperature difference ($24.3-21) =3.3^\circ C$, or less, due to less indoor air temperature. Thermostatic sensor, air change, modulating valve and other options, i.e., overall air-conditioning system, require less work or leads to less hours of
operation due to reduced indoor air temperature and outdoor air temperature. Thus, with a view to obtain the advantage of passive cooling, the design space cooling needs to be considered less than the usual design space cooling for the same area. This approach can be followed by air-conditioning designers, if the indoor and outdoor temperature is already reduced by any other techniques like Living wall, Green roof and Green facade. Otherwise, there will be inappropriate design or there will be over-sized chillers, which often leads to more energy consumption by air-conditioning systems. Finally, the design space cooling load and correlation factor, for the four case-studied buildings, uses the equation before and after Green technologies application. Then the mathematical model developed in section 5.1 has been used to quantify heat gain and energy performance of commercial buildings. A partial part of using temperature data in cooling energy consumption calculation has been demonstrated in Table 5.10.

Table 5. 10: Thermal and Cooling energy performance for one case studied building
(After Living wall application on west-facing wall)

<table>
<thead>
<tr>
<th>Item</th>
<th>Before Living wall application</th>
<th>If Living wall is applied or would apply later on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor air temperature/Ambient temperature, °C</td>
<td>30</td>
<td>Air gap temperature need to be considered due to change of ambient condition</td>
</tr>
<tr>
<td>Air gap temperature as an ambient condition for Living wall, °C</td>
<td>x</td>
<td>25.6-26.2 (from linear regression data obtained from section)</td>
</tr>
<tr>
<td>Ambient temperature reduction, °C</td>
<td>x</td>
<td>30-25.6=4.4</td>
</tr>
<tr>
<td>Indoor air temperature</td>
<td>28</td>
<td>20.7-24.3</td>
</tr>
<tr>
<td>Design indoor air temperature, °C</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Indoor temperature reduction required, °C</td>
<td>7</td>
<td>3.3 or less</td>
</tr>
<tr>
<td>Capacity considered for</td>
<td>1 ton= 2.2 KW for 480 ft²</td>
<td>0.85 ton for 480 ft from</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>--------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>space cooling area</td>
<td>linear interpolation of ambient temperature</td>
<td></td>
</tr>
<tr>
<td>Correlation factor, $\gamma$</td>
<td>9.7</td>
<td>8.9</td>
</tr>
<tr>
<td>Equivalent temperature, $^\circ$C</td>
<td>6.3 determined for west facing wall for a range of temperature range or from using equation developed in Chapter 4</td>
<td>2.6-3 using formulation developed in section 5.2</td>
</tr>
<tr>
<td>% Error encountered in calculation if required</td>
<td>Considered if required from linear regression</td>
<td>Considered if required from linear regression</td>
</tr>
<tr>
<td>Weighted average, $ETTV_0$</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>ETTV of west facing wall</td>
<td>31</td>
<td>25.9</td>
</tr>
<tr>
<td>Total ETTV of all wall</td>
<td>98.5</td>
<td>93.4</td>
</tr>
<tr>
<td>Annual cooling energy consumption $E_c$ (MWh/yr)</td>
<td>409</td>
<td>360</td>
</tr>
<tr>
<td>% Reduction of cooling energy due to Living wall on west-facing wall</td>
<td>$x$</td>
<td>11.98</td>
</tr>
</tbody>
</table>

Finally all of the quantification conducted in the research can be summarised as of the following:

A. Quantification of heat gain and energy performance in presence of Living wall

After thermal performance observation, it can be concluded that equivalent temperature, internal air and air gap temperature is reduced due to Living wall. All of these temperature values affect ETTV and design space cooling load. Finally ETTV and correlation factor affects annual cooling energy consumption.

B. Quantification of heat gain and energy performance in presence of Green facade

Leaf area index LAI, Light extinction coefficient K and Incident solar radiation, affect total solar radiation behind canopy. All of the above affect the external shading coefficient due to
plants. External shading coefficient affects the conduction heat gain part of ETTV of wall or radiation heat gain part of ETTV, depending on application. Finally, it affects ETTV and corresponding design space cooling load considering the correlation factor as a linear relation function of design space cooling load during design space calculation. ETTV and correlation factor affects annual cooling energy consumption.

C. Quantification of heat gain and energy performance of Green roof

After thermal performance observation, it can be concluded that Green roof surface temperature, internal surface temperature of roof and internal air temperature of room are reduced due to Green roof. Due to roof surface temperature, the outside total heat transfer coefficient between Green roof and ambient air, $h_{0g}$ is reduced. $U_g$ and $h_{0g}$ affect roof heat gain. Roof heat gain can be added with envelope heat gain in an integrated building heat gain equation. This heat gain affects total heat gain and corresponding design space cooling load considering the correlation factor as a linear relation function of design space cooling load during design space calculation. Finally, total heat gain and correlation factor affects annual cooling energy consumption.

The quantification of energy performance by Living wall on west-facing wall and Green facade on west-facing fenestration can be performed following processes A and B. Living wall and Green roof quantification can be performed following the processes A and C.

5.8 Discussion

5.8.1 The Living wall application

As air gap temperature is less than ambient temperature, so it has a contribution in reducing equivalent temperature of a building wall in the presence of Living wall. The predicted internal concrete surface temperature was also lower in the presence of Living wall system. So, Living wall in an opaque part of building wall reduces wall temperature which has an influence on ETTV of building wall. As the experimental setup was in west-facing wall, so
ETTV of west-facing wall in four case-studied buildings was found lower, as demonstrated in Figure 5.52. Weighted average ETTV of four orientations was 8 to 10 % less compared to a building without Living wall system in west-facing wall. Using the formulation developed in section 5.1.2, the resultant annual cooling energy consumption was 8 to 13 % less, compared to a building without Living wall system as shown in Figure 5.53.

Figure 5.52: ETTV of west facing wall and weighted average ETTV of case studied building before and after Living wall application on west-facing wall

Figure 5.53: Cooling energy consumption before and after Living wall application
5.8.2 Only Green facade system on wall

The calculated total solar irradiation including direct and diffuse behind the Virginia creeper canopy in a Green façade system have been used to determine the predicted shading coefficient of Virginia creeper for the sub-tropical climate of Australia. The relationship between shading coefficient of Virginia creeper and LAI was found exponential. Shading coefficient of Virginia creeper was the highest due to lowest LAI and the lowest was due to the highest LAI as shown in Figure 5.54. This shading coefficient of Virginia creeper acts as an external shading coefficient, when it is used in front of a building wall as an external shading device to shade and cool for the specific orientation of the building wall. Using the mathematical model developed in the section 5.1.3, the heat gain and cooling energy performance of commercial buildings in the presence of Green facade system on west-facing wall has been quantified.

![Figure 5.54: Relationship of LAI and SC of Virginia creeper](image)

From Figure 5.55, it was depicted that weighted average ETTV was reduced due to Green façade system on an opaque part of west-facing wall. The weighted average ETTV was reduced to 8-10 % in each case-studied building. Again, the reduction was significant in west-facing wall and it was between 23-29 % in the case-studied building. Overall, the total annual cooling energy consumption of commercial building was reduced to 9.5-18 % due to Green façade system application on west-facing wall of case-studied buildings, as shown in Figure 5.56.
Figure 5.55: ETTV of west-facing wall and weighted average ETTV of case-studied building before and after Green facade application on west-facing wall

Figure 5.56: Annual cooling energy consumption before and after Green facade application on west-facing wall

### 5.8.3 Only Green facade system on window

The average value of shading coefficient of Virginia creeper was 0.14 and it was considered during heat gain and cooling energy estimation. The total shading coefficient value of the fenestration system was lower as external shading coefficient value due to Virginia creeper’s shading coefficient affected the total shading coefficient as shown in Figure 5.57.
Figure 5.57: The relationship between shading coefficient of window and total shading coefficient in presence of Green facade system

The minimum total shading coefficient value was found 0.028 for glass having shading coefficient 0.2 and the maximum was found 0.12 for glass having shading coefficient 0.86. Therefore, the total shading coefficient of fenestration system was reduced in each case. Using the mathematical model developed in the section 5.1.3, the heat gain and cooling energy performance of a commercial building in the presence of Green facade system on west-facing window has been quantified.

From Figure 5.58, it was illustrated that weighted average ETTV was reduced due to Green façade system on the fenestration part of west-facing wall. The weighted average ETTV was reduced to 16-18 % in each case-studied building. However, the reduction was significant in west-facing wall and it was between 48-60 % in case-studied building. Overall, the total annual cooling energy consumption of commercial building was reduced to 28-35 % due to Green façade system application on west-facing wall of case-studied buildings as shown in Figure 5.59.
5.8.4 A combination of Living wall and Green facade

Using the mathematical model developed in section 5.1.4, the heat gain and cooling energy performance of a commercial building in the presence of Living wall on west-facing wall and Green facade system on west-facing fenestration has been quantified. From Figure 5.60, it was illustrated that weighted average ETTV was reduced, due to Living wall on an opaque part of west-facing wall and Green façade on west-facing fenestration (combination of both). The weighted average ETTV was reduced to 21-23% in each case-studied building. However, the
reduction of ETTV was significant in west-facing wall and it was between 65-70 % in case-studied buildings. Overall, the total annual cooling energy consumption of commercial buildings was reduced to 37-40 % due to Green façade system application on west-facing walls of case-studied buildings as shown in Figure 5.61.

![Graph showing ETTV and cooling energy consumption](image)

**Figure 5. 60: ETTV of west-facing wall and weighted average ETTV after combined Living wall and Green facade application**

**Figure 5. 61: Annual cooling energy consumption before and after combined Living wall and Green facade application**

### 5.8.5 Combination of Living wall and Green roof

Using the mathematical model developed in the section 5.1.5, the heat gain and cooling energy performance of a commercial building in the presence of Living wall in west-facing wall and Green roof has been quantified. The calculated value of heat gain for a concrete roof
was within the range 20-40 W/m$^2$ whereas estimated heat gain in the presence of a Green roof was within 4-10 W/m$^2$ as demonstrated in Figure 5.62, with varying ambient temperature condition. On average, total heat gain after application of Living wall on west-facing wall and Green roof on concrete roof has shown a reduction of heat gain around 10 to 12 (W/m$^2$) in a number of building case studies as shown in Figure 5.63. Figure 5.64 demonstrated that 130-164 MWh/yr cooling energy can be saved which can contribute around 25-32% annual cooling energy consumption. This amount of saving can be obtained by using Living wall in west-facing wall and Green roof. Figure 5.65 showed that cooling energy can be saved annually, 3-8 (KWh/m$^2$pa) based on wall and roof area, while 5-12 (KWh/m$^2$pa) savings can be made based on space area as shown in Figure 5.65. However, the reduction would be greater if Living wall was placed on east, north and south sides of building as well.

Figure 5.62: Concrete roof and Green roof heat gain variation with ambient temperature

Figure 5.63: Heat gain of case-studied building before and after Living wall Green roof application
Chapter 5

Figure 5. 64: Annual cooling energy consumption before and after Living wall and Green roof application

Figure 5. 65: Annual cooling energy consumption based on wall and roof area, and based on space area before and after Living wall and Green roof application

Conclusion

External Living wall in an opaque part of west-facing wall can reduce 10-12% cooling energy consumption of a commercial building whereas Green facade system on an opaque part of west-facing wall can reduce 10-18% of cooling energy consumption. Again, Green facade system in fenestration system of west-facing wall can reduce 28-35% cooling energy consumption of a commercial building. Examining the results, it is clear that an external Living wall application on an opaque part of west-facing wall and an extensive Green roof made up of Australian native plants can reduce 15-20% cooling energy consumption of
commercial buildings in the sub-tropical climate of Australia. Living wall in other walls (North, South and East) would certainly increase the energy saving. However, recorded data from a combination of Green roof and Living wall setup may vary in different parts of Australia, due to variations of solar radiation and weather condition. The best results would be obtained from a combination of Living wall system in the opaque part of west-facing wall and Green facade system in fenestration system, made up of deciduous planting for west-facing wall. This combination showed a reduction of 35-40% of cooling energy consumption of a commercial building. So, the results demonstrate the effectiveness of using both Green roof and Living wall for cooling energy saving. Furthermore, the formulations developed in Chapter 4 have been used in the presence of green applications with changes of some heat gain parameters for heat gain and cooling energy quantification in Chapter 5. The modified formulations used in Chapter 5 demonstrates that the heat gain equation based on ETTV and steady-state heat gain by roof, can be used for estimation of energy consumption.
Chapter 6: Conclusions and Recommendations

Summary

_in this chapter, key findings of the study have been outlined first. Then contributions to knowledge and practice have been described. The limitations and barriers for implementation of these energy-efficient approaches have been explained. Finally, suggestions for future work have been given and conclusions have been drawn._

6.1 Summary of the key findings

6.1.1 Development of ETTV equations for the sub-tropical climate of Australia

In this study, ETTV equations for the sub-tropical climate of Australia have been formulated. Computed coefficients of ETTV have been examined and the total computed value of ETTV has been found within the range 24-42 W/m² which is valid for commercial buildings in the sub-tropical climate of Australia. The maximum ETTV determined from this study is 42 W/m². This can be used as benchmark value for energy efficient envelope design. A set of coefficients (Table 4.11) has been determined from extensive analysis of hourly heat gain. The new formulations of ETTV for different orientations of building (4.19-4.29) have been developed. A close relationship between ETTV and air-conditioning energy consumption indicates that the ETTV approach can be adopted to regulate and to quantify annual space cooling energy consumption of commercial buildings (Figure 4.22 and 4.23). From the relationship of ETTV and space cooling energy consumption, it has been observed that a reduction of 5-6 (W/m²) will provide 60-65(KWh/m²) reduction of cooling energy in number of case-studied buildings (Figure 4.23) using the newly developed formulation. For multi-storied commercial buildings with highly insulated roofs, ETTV value has significant contribution in cooling energy consumption analysis that leads to energy efficiency improvement (Section 4.6.4, and 4.6.5). ETTV-based cooling energy estimation derived from the newly-developed formulation rather than other commercial software such as Trane Trace, provides more accurate estimation of cooling energy consumption, when it is compared with
actual consumption (Section 4.6.5). Furthermore, ETTV and steady-state heat gain of a roof in an integrated heat gain model has a significant contribution towards accurate estimation of heat gain. This leads to accurate cooling energy consumption analysis of high-rise, mid-rise and low-rise commercial buildings with insulated or uninsulated roofs (Section 4.6.5, 4.6.6 and 4.6.7). The relationship between ETTV and Green applications in a modified formulation for sub-tropical climate of Australia is another key finding (equations 5.6, 5.11, 5.15, 5.18 and 5.27; Section 5.1). The suitability of these equations is also proven by using them in quantification of thermal and energy performance of commercial building (Sections 5.1, 5.7 and 5.8).

6.1.2 Thermal and Energy performance by Green technologies

Change of ambient condition due to Living wall application affects the cooling energy consumption of commercial buildings. Due to Living wall, air gap temperature was comparatively lower than ambient temperature. This air gap temperature is a changed ambient condition for Living wall system. On an average, the temperature of air gap was 4.4-5 °C less than ambient temperature (Section 5.6). This change of ambient condition affects the cooling energy consumption (Section 5.7). The indoor air temperature measured from the Green shed in a controlled condition, during spring and summer time, was between 21 and 24 °C. This demonstrates that the indoor temperature was almost the same as the indoor design condition for HVAC design of commercial building application. This is an indication of using Living wall on buildings which may reduce indoor air temperature and reduce the need for air-conditioning during spring and summer months. On average, temperature reduction of 3.8-4.2 °C at the internal surface of concrete wall (Section 5.5) and reduction of 6-10 °C at the internal surface of concrete roof can be obtained (Section 5.5) by the use of Living wall and Green roof. The temperature reduction of air gap, ambient and internal air temperature affect the cooling energy consumption of building as has been investigated in this study (Section 5.7). External shading coefficient due to the use of deciduous plants on west-facing wall or west-facing window has demonstrated that they have the significant potential of cooling energy reduction of commercial buildings. All of the temperature reduction in ambient, wall surface, roof surface, indoor air temperature, and external shading coefficient due to planting, affect the ETTV and design space cooling load that subsequently reduce the cooling energy consumption of commercial buildings.
In the case of ETTV reduction, different applications have a different impact on cooling energy saving, as has been observed from the number of case-studied buildings (Section 5.8). A reduction of 5-5.2 (W/m^2) of ETTV of west-facing wall and a reduction of ETTV 1.9-2 (W/m^2) for the whole building (weighted average) can save 10-12% cooling energy consumption of a commercial building if Living wall is placed on west-facing wall. In case of Green facade on west-facing wall, a reduction of 6-6.5 (W/m^2) of ETTV for west-facing wall and reduction of 2.2-2.4 (W/m^2) for the entire building have been observed and the resulted cooling energy saving was 10-18%. The Green facade on west-facing window can provide cooling energy saving of 28-35% where the ETTV reduction of west-facing wall was 14-15 (W/m^2) and weighted average ETTV reduction would be 5-5.3 (W/m^2). The most significant reduction of cooling energy has been observed for a combination of Living wall on west wall and Green facade on window. In this case, a reduction of 18-20 (W/m^2) of ETTV of west-facing wall and weighted average ETTV of 7-8 (W/m^2) can be achieved and eventually can save 35-40% of cooling energy consumption. On the other hand, a combination of Living wall and Green roof can save 25-32% of cooling energy where the weighted average heat gain (Combination of ETTV for envelope and steady state heat gain of roof) reduction was 12-13 (W/m^2).

To sum up, the investigation of energy performance of different combinations of Green technologies demonstrated that they have a significant contribution to thermal and cooling energy saving. The estimated energy saving of different applications is summarised in Table 6.1.
Table 6.1 Percentage of annual cooling energy saving in different applications

<table>
<thead>
<tr>
<th>Application of Green technology</th>
<th>Percentage (%) of Annual cooling energy saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Living wall application on west facing wall</td>
<td>10-12</td>
</tr>
<tr>
<td>External Green facade application on west facing wall</td>
<td>10-18</td>
</tr>
<tr>
<td>External Green facade application on west facing window</td>
<td>28-35</td>
</tr>
<tr>
<td>Combination of external Living wall on west facing wall, and external Green facade of west facing window</td>
<td>35-40</td>
</tr>
<tr>
<td>Combination of external Living wall on west facing wall and extensive Green roof on top of roof</td>
<td>25-32</td>
</tr>
</tbody>
</table>

6.2 Contribution to knowledge

6.2.1 ETTV equations and coefficients

The original ETTV equation was developed by Chua and Chou (2010a). They used the same equation for all walls and orientations. In the present study, the formulation has been developed for individual orientations. Equations developed by Chua and Chou (2010a) have been modified for south and east-facing orientations due to the effect of negative heat gain. Furthermore, the conduction heat gain part is now dependent on U value of wall rather than dependent on more variables if window-to-wall ratio is constant for any orientation. These have been demonstrated for south and east-facing walls. The conduction heat gain part can be written for south and east-facing walls as a function of U value of wall (equation 4.27 and 4.28). Here, the predetermined coefficients $C_S$ and $C_E$ are constant as well.

In the original equation of ETTV (equation 4.4), the conduction heat gain part of window depends on window-to-wall ratio, temperature difference and U value of window. This study develops the conduction heat gain part of window as a function of U value of window.
Conduction heat gain for any orientation of window is dependent on U value of window if WWR is constant (equation 4.29). Conduction heat gain part of window for any orientation can be written as a function of U value of window as shown in equation (4.29). Here the predetermined coefficients $C_{DT}$ and $D_{DT}$ are constant as well.

The coefficients that have been determined for ETTV formulation can be used to formulate ETTV and ETTV value for newly-designed and existing buildings in sub-tropical and tropical climates of Australia.

The process followed in this study to determine coefficients, new formulation and ETTV value can be implemented to determine coefficients, new formulation and ETTV value determination of temperate and hot, humid climates of Australia.

The maximum permissible ETTV value determined from the study is 42 (W/m²). This ETTV value can be used as a benchmark value for the improvement of energy efficiency of different types of high-rise and mid-rise commercial buildings located in sub-tropical and tropical climate locations in Australia.

6.2.2 ETTV-based energy estimation

Different consultancy firms use different commercial software which has some default values of some parameters. Sometimes these values are considered or sometimes are ignored by HVAC designers. These default values have an impact on cooling energy estimation of commercial buildings. In the present study, the annual cooling energy consumption has been computed by the ETTV value derived from the newly developed formulations of individual orientation. For comparison, cooling energy was also calculated using commercial software Trane Trace. The results demonstrated that ETTV based estimation is more closely matched with the actual consumption and the software simulated value is far away from the actual consumption, as has been discussed in section 4.6.4 and section 4.6.5 in Chapter 4. Thus, overestimation of cooling energy (by software) leads to increased capacity of chillers which consume more energy.
6.2.3 Inclusion of roof heat gain in total heat gain and cooling energy estimation of buildings

In the present study, it has been demonstrated that ETTV can contribute significantly to determine accurate cooling energy estimation for a high-rise building with highly insulated roof. However, it is also established and proved that a building integrated heat gain model contributes significantly to cooling energy consumption of mid-rise or low-rise commercial buildings, where roof area is significant and uninsulated. The initial model developed by Chua and Chou (2010a) for annual cooling energy consumption of commercial building has been modified by inclusion of roof heat gain. The results discussed in section 4.6.6 and 4.6.7 in Chapter 4 proved that cooling energy estimation by an integrated heat-gain model equation (4.30) provides more accurate estimation. The previously-developed Roof Thermal Transfer Value is applicable to roof with skylight, although it may not be applicable to an opaque roof as there is no skylight. Instead of using combined ETTV and RTTV, the building integrated heat-gain model combining ETTV and steady state heat gain provides more option and accuracy to compute heat gain and cooling energy estimation of commercial buildings. The combined heat-gain model developed in this study is also significant in the case of cooling energy estimation in presence of Green application i.e., Living wall and Green roof combination on commercial building.

6.2.4 External shading coefficient

The determination of external shading coefficient of straight and inclined overhang located at a distance from the top of window is significant for ETTV formulation. Inclusion of the shading coefficient affects ETTV formulation, which provides the option to reduce solar heat gain by wall and window. In this study, external shading coefficients for wall and window have been determined (Section 4.4.3, Table 4.9 and 4.10). The value of external shading coefficient for wall due to straight overhang is significant for self-shading buildings. In self-shading buildings, the extended straight portion of the top floor acts as external shading devices for the wall and window of the next floor. The future construction of self-shading commercial buildings in Australia would be another option in energy-efficient envelope construction design which will lead to less solar heat gain and subsequently less cooling.
energy consumption for a sustainable building operation. Inclusion of the external shading coefficient of wall and window in ETTV formulation is a new concept and provides the option to use ETTV formulation to compute heat gain and corresponding cooling energy consumption estimation in case of Green technologies use i.e., Green facade system on wall and Green facade system on window of buildings. In a highly urbanised and dense environment, it is common to have adjacent buildings shading another. This will inadvertently affect the heat gains through the façade. The process adopted to determine external shading coefficient due to overhang condition in ETTV can be followed for inclusion of an inter-block shading coefficient to consider the shading from neighbouring buildings.

6.2.5 Investigation of application of Living wall, Green facade and Green roof

Wong et al. (2009) used the TAS simulation software to determine minimum and maximum temperature of the room, mean radiant temperature and surface temperature in presence of Greenery. In this study, thermal performance of Living wall and Green roof has been investigated theoretically as well as experimentally. After validation of the model, it has been used to quantify predicted thermal performance of real building application. This estimation approach can be conducted to determine thermal performance of Living wall and Green roof in any construction.

In this study, the mathematical models (equations 5.1, 5.6, 5.11, 5.15, 5.18 and 5.27) are developed for heat gain calculation in the presence of Green applications (i.e., Living wall; Green facade; combined Living wall and Green facade; and Living wall and Green roof). These formulations have been derived from a newly-developed formulation of ETTV in Chapter 4 and the addition of equation for steady-state heat gain by roof developed by Suehrcke et al. (2008). The heat-gain models developed are the first of their kind and therefore can be considered unique and can be used for further investigation of thermal performance of Living wall, Green facade, Green roof, combination of Living wall and Green facade, and combination of Living wall and Green roof on real buildings with different construction.
The amount of reduction of annual cooling energy consumption in the presence of Green applications (i.e., Living wall, Green facade, Green roof technologies) have been demonstrated in this study (Section 5.8). To the best of the author’s knowledge, the quantification of cooling energy performance in the presence of Living wall, Green facade, and Green roof in different combinations (Living wall only, Green facade on wall, Green faced on window, Living wall and Green facade, Living wall and Green roof) using Australian native plants has not been investigated for Australia.

Literature reports the application of Living wall on south-facing wall. In this study, the west-facing wall has been selected for Living wall application. It has been demonstrated that application of Living wall or Green facade on west-facing walls of commercial building would be significant as results from the study demonstrate significant saving of cooling energy consumption (Section 5.8).

6.3 Contribution to practice

6.3.1 ETTV as a Building Energy code

The information relevant to Envelope Thermal Transfer Value (ETTV) has not been stated in the Building Code of Australia (BCA, 2011; NCC, 2012). Different countries adopt ETTV as an energy-efficient envelope code as has been listed in Chapter 2. ETTV values determined in this study can be used as an energy-efficient building energy code for promoting energy efficiency during design and operation of commercial buildings. This maximum permissible ETTV value can be considered as a benchmark and any envelope design or modification complying with this bench mark value enhances the use of energy-efficient approaches among building designers, architects and engineers. It is better to control the energy consumption of buildings using the energy-efficient energy code during the design stage of the building rather than in the operation stage because renovations of buildings are sometimes quite expensive and time consuming. So the decisions made early in the project have a strong influence on the life cycle cost of the building.
6.3.2 ETTV and climate-specific design and planning of building

It has been established in the present study that the ETTV of individual orientations is not the same. The study conducted in the sub-tropical climate of Australia has a significant contribution in climate-responsive planning and design of building. Any passive cooling techniques such as shading by trees, Living wall and Green facade on wall and windows reduce the heat gain of west-facing wall. The maximum permissible value for each orientation can play a significant role in reduction of heat gain and corresponding cooling energy consumption. If building designers follow the maximum permissible value of ETTV of individual orientations (in this case west-facing wall for a sub-tropical climate) as a building energy code, then it would encourage designers to design the building with appropriate energy-efficient techniques for that orientation. These energy-efficient techniques include Green applications (e.g., Living wall, Green facade technologies), that can reduce the ETTV of specific orientation. This affects the total ETTV and cooling energy saving as well. For other climates, such as temperate, hot and humid, etc., the permissible value of ETTV of each orientation also leads to energy-efficient climate responsive design and planning of the buildings. To sum up, it can be concluded that the ETTV of individual orientations has a great influence on climate-specific planning and design of building.

6.3.3 Living wall, Green facade and Green roof application

Many experimental investigations of Living wall and Green roof are discussed in the literature review section (Chapter 2). The cost of construction and maintenance of Green technologies is comparatively higher than other energy conservation measures, as research is still ongoing into the construction materials, suitable plants and climate suitability of these technologies. However, the amount of thermal energy and more significantly environmental benefit are extremely higher than any other energy conservation measures. Therefore, before installation of any Living wall, Green facade and Green roof on real building, it is better to check their thermal performance in a controlled condition. This option provides opportunities to investigate their thermal and energy performance. It would not be a wise decision to purchase any Living wall and Green roof application and install it in the building without investigation of thermal and energy performance in a controlled condition to predict the
future energy saving of the building. Thus it can be concluded that a real experimental setup for the thermal and energy performance of climate specific Living wall, Green facade and Green roof application in a controlled condition is an excellent approach where the manufacturers, building owners, operators and designers can rely on the results to obtain the next decision on implementation.

In Australia, most of the commercial buildings don’t have any Living wall, Green facade and Green roof application. Some European countries are investigating the Green applications and some European countries mandated the use of Green applications (Your home technical manual, 2010). Linz, in Austria requires Green roofs on all new residential and commercial buildings with rooftops larger than 100m² as a part of their building code act (Your home technical manual, 2010). German Green roof building has been encouraged by the Federal Nature Protection Act, whereas Australian examples are less common. However, in 2007 a national organisation was formed to promote Green roofs (Your home technical manual, 2010). Brisbane City Council included Green roofs in its proposed action plan for dealing with climate change (Your home technical manual, 2010). In city areas, the roof top of commercial buildings can be made greener to reduce urban heat island effect and to obtain thermal comfort. Although some applications have been reported, the application of external Living wall systems on commercial buildings are very limited in Australia. The study conducted in this research indicates that the covering of one orientation of commercial buildings (in this case west-facing wall) by Living wall or Green facade or a combination of both, can significantly reduce cooling energy consumption. The higher thermal and energy benefit can be obtained when the Living wall application will be placed on the concrete wall of the building. In the present study, the combination of Living wall on west-facing wall and Green roof on top of roof, demonstrated significant potential of the cooling energy saving of commercial buildings. This study also demonstrates that a combination of Living wall and Green facade on west-facing wall is another combination which has the significant prospect of cooling energy-saving of building as well. The amount of cooling energy-saving potential due to the use of different combinations of Green application is an appropriate finding that can promote the implementation of these types of application on commercial buildings to obtain thermal, energy and environmental benefit in an occupied and fast growing city centre. Mitigation of urban heat island effect and rain water harvests are the other major benefits that
can be achieved with energy benefits after application of these applications on commercial buildings in cities of Australia.

6.4 Limitations of the study

The formulation of ETTV developed in this study is applicable to subtropical and tropical climates. However the formulation can be developed for other climate conditions as well, using the approach adopted to determine coefficients and formulation. Once the climate-specific formulation is developed and some case studies have been examined, then its use in heat gain and cooling energy estimation will provide various advantages.

The control shed and Green shed used in the experimental setup were made of steel structure, which sometimes provides incorrect data for analysis as change of ambient conditions (such as too hot outside in the earlier part of the day and rain in the later part of the day) at the same day of the measurement, affects the temperature data of different points of steel and the internal air of Green shed. Due to the excellent thermal conductance properties of steel, a scenario occurs that affects the temperature measurement. The experimental setup can be made of different wall constructions which may provide more accurate data and results. Thermal transmittance values of Living wall and Green roof have been determined based on available literatures and the supplier’s information, which may affect the analysed results. An authentic standard value of any type of construction of Living wall and Green roof is required to make the analysis more accurate. In this study, external shading coefficient of plants due to Green facade application has been determined using available solar data and mathematical modelling rather than using pyranometer for accurate measurement, which is another limitation of this study. The radiation behind the canopy needs to be investigated by pyranometer to compare it with the mathematically-analysed solar radiation behind the canopy, which will provide more accurate external shading coefficient value.
6.6 Future work

The benchmark value of ETTV would be different for different climate zones. Therefore more investigation is necessary in regulating the ETTV of commercial buildings to produce a more energy-efficient design approach. At the early design stage, certain design modifications in envelope need to be considered to ensure reduction of ETTV. The formulation of ETTV for self-shaded and inter-block shaded commercial buildings to design an energy-efficient envelope would be future work for researchers for different climate zones of the world.

Determination of external shading coefficients in the presence of perforated shutters in front of fenestration is another consideration that can be investigated for reducing heat gain of commercial buildings.

Optimisation of building envelope parameters is critical for buildings’ energy performance and human comfort as well. Optimisation of opaque components and visible components of the building envelope can contribute significantly toward optimum energy consumption of buildings. Researchers from different countries are emphasising their effort on reduction of Green house gas emission caused by buildings. Optimum envelope components, for example, optimum insulation thickness in walls, have the potential to reduce building energy consumption and hence to reduce CO₂ emission. In this context, the effect of optimum insulation thickness on the environment due to optimum energy consumption obtained from ETTV based cooling energy consumption of buildings can be analysed at the initial design stage, which requires further investigation in future.

Determination of thermal transmittance value of Green technologies product (Living wall, Green roof) of a manufacturer is still unknown to experts in many cases. The future research direction of these applications would be evaluation and establishment of thermal transmittance value and other technical standards such as temperature sustainability for different climatic conditions and durability of construction materials, which need to be investigated to obtain further thermal and energy performance.
Research on Green facade system on window is still in its experimental stage in many cases. The application of Green facades on fenestration systems through analysis of solar radiation needs to be investigated to establish more significant savings of cooling energy. The accurate measurement of solar radiation behind the canopy in a real experimental conditions using pyranometer and using native deciduous plants for a longer period of time, can be the future research for application of these types of Green applications.

The seasonal variation of heat flux, corresponding to cooling energy requirements of different types of Living wall, Green facade and Green roof for external application on buildings, would be the prospective investigation for researchers. Investigation of air gap temperature and ambient temperature by varying the distance from the building wall can be one research direction for more cooling energy saving of commercial buildings. Insulating the surrounding of air gap and then investigation of thermal performance would be another option in this case. The indoor air quality, for example the amount of CO₂ present in indoor air conditions, can be investigated through the Living wall study. This can be achieved by supplying air from an outside setup made of fans in front of Living wall system. Occupants’ productivity, thermal comfort, and energy saving investigation in a Green building made of Living wall and Green roof can be the most emphatic directions for further research of Living wall and Green roof applications. Using rain water from the Green roof system to improve the supply of fresh water in a city, water sensitive urban design, storm water management from Living wall and roof for irrigation or other purposes can be other future work for researchers.

The comprehensive life cycle cost analysis, payback period and the feasibility study of these applications made of different constructions on different types of buildings can be future projects of researchers. Research on using native plants sustainable for different climate conditions, low cost construction and recyclable material use in Living wall, Green facade and Green roof applications can be another prospective work for researchers.

6.7 Recommendations and Conclusions

The study on the ETTV, Living wall, Green facade and Green roof demonstrated that these energy efficient approaches in the design stage of new buildings and operation stage of existing buildings have the significant contribution of energy saving for commercial
buildings. The approaches studied in this research can stimulate future investigations of the energy-saving potential of these approaches. The Authority of Building Code of Australia, (BCA) and Australian Institute of Refrigeration and Heating, (AIRAH) may consider further evaluation of the appropriateness of ETTV adoption. The investigation of temperature data for a longer period of time (at least two years) and different climatic conditions (Spring, Summer, Winter and Autumn) can be observed for obtaining more realistic results in the case of real building application. Development of an appropriate experimental setup for investigation of thermal and energy performance of different types of Living wall, Green facade and Green roof system manufactured by different manufacturers can overcome the risk of their long-time sustainability. Building designers, owners and operators should factor the maintenance costs for implementation of Living wall, Green façade and Green roof into an effective sustainable technology plan. The rules and regulations for application of these Green applications on different types of buildings is a major task for government, building code boards, designers and architects. The awareness among people of using this type of technology may lead directly to obtain less greenhouse gas emissions and contribute to the achievement of the goal ‘Zero Carbon’, Australia.
References


eQUEST Introductory tutorial v.3.64, 2009, p. 15-21.


Meier, A., Olofsson, T., & Lamberts, R. (2002). What is an energy efficient building? 9th National Meeting of Environmental Technology Built, Foz do Iguacu Parana, Brazil 7-10 May, 2002


Presentation transcript 70.2 Energy Efficiency in http://www.slideshare.net/arkam_slideshare/green-building-sustainability accessed on January 12, 2012


Appendices

Appendix 1: Some of the pictures of envelope of Eco-centre, Nathan, QLD

Figure A-1: (a) Internal space of eco-centre with daylight comes from glass on specific orientation, top ventilation glass and top of roof; special construction of wall by rammed earth wall

(b) Class room with daylight comes from specific orientation

(c) Conference room with special duct system by clothes and daylight from specific orientation

(d) Entrance of the Eco-centre made of glass and wall made of rammed earth wall
Appendix 2: Building materials of Eco-centre, Nathan

Building Materials /Wall Construction

Composition of rammed wall is 80 % Sand and clay (Clay + Binding agent), 10 % Crusher dust, 5 % Cement and 5 % Ash. Clay and binding agent is hand rammed on site in large wooden moulds.
Appendix 3: Daylight control in Eco-centre, Nathan

Figure A-3: (a) Smart glass on building facade for day lighting  
(b) Smart glass on top of wall  
(c) Ventilation on envelope
Appendix 4: Simulation steps and Screeshot of steps in eQUEST wizard

Simulation steps

Step 1
In model building simulation, the first step was to select building type. For simulation, high rise commercial office building has been considered. The weather file has been selected for the specific location for example Brisbane. However, the specific site has been selected from the DOE2 weather data file available online and connected them with eQUEST energy simulation tool. Building area, above grade, analysis year, daylighting control and usage details have been inserted as an initial input for the model building simulation.

Step 2
In this step, model building footprint considering the zoning pattern has been selected for HVAC zoning of the model building. Plan view direction, Perimeter zone depth, area per floor, floor to floor height have been given as an input for model building simulation.

Step 3
In this stage, construction details of building envelope have been inserted as an input to eQUEST energy simulation tools. Construction details include both grade walls and roof surfaces with details input regarding the exterior finish and colour, exterior insulation, ground floor exposure and construction and interior finish.

Step 4
At this stage, data relevant to ceilings, vertical walls and floors including internal finish and construction have been included in the wizard screen.

Step 5 and 6
Details information regarding the door type, height and width of door with construction details, window glass type, percentage of window floor to floor and details construction

Step 7 and 8
In this stage, activity areas allocation is the main input for the eQUEST wizard. Design maximum occupancy (square feet/person) have been obtained from collected data of
consultancy firms and then inserted in eQUEST. Area type includes office, corridor, lobby, conference room, rest rooms, mechanical and electrical rooms.

Step 9
At this stage, main scheduling information has been inserted in eQUEST energy simulation tools for model building simulation. The building operation hour has been considered 12 hours of operation per day from Monday to Friday.

Step 10 to Step 41
Various information regarding HVAC system definitions, HVAC zones temperature and air flows, HVAC system fans, HVAC operation such as operating hours and other relevant information have been inserted in eQUEST energy simulation tool.

Some of the screenshots of simulation steps (1-41) are given below

Figure A4-1: Building information insertion in eQUEST
Figure A4-2: HVAC zoning and perimeter selection

Figure A4-3: Insertion of Building envelope construction
Figure A4-4: Insertion of building interior constructions

Figure A4-5: Insertion of building exterior doors information
Figure A4-6: Insertion of information of exterior windows

Figure A4-7: Insertion of data relevant to activity areas allocation
Figure A4-8: Insertion of data relevant to occupied loads by activity area

Figure A4-9: Insertion of building operation schedule
Figure A4-10: Insertion of HVAC system definitions

Figure A4-11: Insertion of temperatures and air flows data
Figure A4-12: Insertion of data for HVAC system fans

Figure A4-13: Insertion of data of HVAC system fan schedules
Figure A4-14: Insertion of data of HVAC zone heating, vent and Economizers

Figure A4-15: HVAC system hot/cold deck resets
Figure A4-16: Insertion of information of cooling primary equipment

Figure A4-17: Insertion of data relevant to water cooled condenser and cooling tower
Figure A4-18: Chilled water system control and schedule

Figure A4-18: Information on heating primary equipment
Figure A4-19: Insertion of information on hot water control and schedule

Figure A4-20: Insertion of information of water heating
Figure A4-21: Insertion of building address details

Figure A4-22: Top, bottom and interim layer of model building
Appendix 5: Conversion SD Wizard to DD Wizard

After insertion of all data in the eQUEST tool, the baseline run of the model building has been conducted. However, for better control, Schematic design wizard has been converted to detailed data edit wizard for editing purposes. Building envelope and shell component details, lighting and equipment details and HVAC details have been edited and confirmed in detail data edit wizard. Then the whole building model has been viewed in schematic data wizard using the shell multiplier options in edit option of shell data. To sum up, conversion of schematic to detail data edit input includes general shell information, perimeter, building envelope construction, exterior windows, building operation schedule, activity areas allocation, zone definition group, non-HVAC end users model, interior lighting loads, office equipment loads, miscellaneous loads and exterior lighting loads.

Figure A5-1: Selection of design development wizard
Figure A5-2: Selection of building shell components

Figure A5-3: Editing of building shell information
Figure A5-4: Loading (running) file of the model building

Figure A5-5: 2D view of the model building in DD wizard
Simulation of base case

In this stage, simulation of the base model building has been conducted. The results of the base building provide two options to retrieve the final results of the simulation. They are:

(a) View summary results or reports
This result provides detailed energy consumption of different elements including space cooling energy consumption monthly and yearly.

(b) View detailed simulation output file
This result provides hourly heat gain by wall and window according to the selection for wall and window in ‘hourly report block’ in eQUEST.
Figure A6-1: Selection of ‘hourly report block’ and ‘hourly results series’

Figure A6-2: Selection of results after simulation
Figure A6-3: Hourly results selection in eQUEST

Figure A6-4: Hourly Results in Excel file from eQUEST Output
Appendix 7: Hourly heat gain for each parametric simulation

Parametric Run

To perform the parametric run, the option parametric run has been selected from the tools menu and then “Create Parametric Run” has been created for the wall and window type of different constructions. In each parametric run of wall or window construction, only one type of wall or window has been considered to retrieve the hourly heat gain data and to investigate the energy performance of each construction. So, the steps in parametric run are:

(a) Define parametric run
(b) Define one parameter in each parametric run
(c) Simulate parametric runs
(d) Analyse the result of each parametric run

The following inputs are considered during parametric simulation:

(a) U value for walls in each parametric simulation

For different types of wall construction, the details’ information has been studied and selected in layers during the initial input for eQUEST simulation for base case. However, the wall construction details have been changed in “EL1 Construction layer” by changing the U value input EL1 construction layers under Building Shell category.

(b) Window glass type selection for each parametric simulation

Different types of reflective glasses for windows have been selected from the eQUEST glass library, which have the similar characteristics and close matching with the AIRAH handbook. During each parametric simulation for windows, only one type of glass has been selected. So, the hourly heat gain by window due to conduction and solar heat gain completely relates to the transmissibility, shading coefficient, and U value of glass.
Finally, yearly heat gain data and cooling energy consumption for each specific construction has been retrieved in individual “hourly heat gain results”. For example, three-hourly heat gain results have been obtained for three parametric simulations of three different types of construction for wall or window.

Figure A7-1: Selection of wall and window of specific orientation of the building
Figure A7-2: Selection of U value of specific orientation of the building

Figure A7-3: Change of U value of specific orientation of the building
Figure A7-4: Hourly report for wall conduction, window conduction and solar heat gain

Figure A7-5: Hourly report for wall in Excel file
Figure A7-6: Hourly report for window in Excel file
Appendix 8: Some of the data of shopping centres of capital Dhaka of Bangladesh

<table>
<thead>
<tr>
<th>Location in Dhaka, Bangladesh</th>
<th>Calculated (MWh/yr)</th>
<th>Actual (MWh/yr)</th>
<th>Total capacity of chiller (KW)</th>
<th>Calculated EETV (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bashundhara City</td>
<td>960</td>
<td>940</td>
<td>3520</td>
<td>59</td>
</tr>
<tr>
<td>Motaleb Plaza</td>
<td>470</td>
<td>430</td>
<td>1540</td>
<td>28</td>
</tr>
<tr>
<td>Karnaphuli Garden City</td>
<td>302</td>
<td>292</td>
<td>990</td>
<td>23</td>
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</table>

Appendix 9: Data for determining Building Heat Gain (W/m²) for both the Office and administrative buildings

<table>
<thead>
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<th>No</th>
<th>Characteristics</th>
<th>Data for Office Building</th>
<th>Data for administrative Building</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Plan View (for example, square/rectangular)</td>
<td>rectangular</td>
<td>rectangular</td>
</tr>
<tr>
<td>2</td>
<td>Total Area of building (L X W) m²</td>
<td>6000 sq m</td>
<td>3618 sq m</td>
</tr>
<tr>
<td>3</td>
<td>Numbers of floors</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Floor Area (m²)</td>
<td>6000 sq m</td>
<td>3618 sq m</td>
</tr>
</tbody>
</table>

For Wall

<table>
<thead>
<tr>
<th>No</th>
<th>Characteristics</th>
<th>Data for Office Building</th>
<th>Data for administrative Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Type of material used in wall (Concrete/Red brick/Brick etc)</td>
<td>insulated cmu</td>
<td>cmu with Limestone</td>
</tr>
<tr>
<td>6</td>
<td>Total Area of Opaque Walls, Aw (m²)</td>
<td>3680 sq m</td>
<td>1566 sq m</td>
</tr>
<tr>
<td></td>
<td>Area of North facing wall, An (m²)</td>
<td>875.2 sq m</td>
<td>239.62 sq m</td>
</tr>
<tr>
<td></td>
<td>Area of South facing wall, As (m²)</td>
<td>875.2 sq m</td>
<td>239.62 sq m</td>
</tr>
<tr>
<td></td>
<td>Area of East facing wall, Ae (m²)</td>
<td>964.81 sq m</td>
<td>543.37 sq m</td>
</tr>
<tr>
<td></td>
<td>Area of West facing wall, Awe (m²)</td>
<td>964.81 sq m</td>
<td>543.37 sq m</td>
</tr>
<tr>
<td>7</td>
<td>Total Area of Glazing, Ag (m²)</td>
<td>188.32 sq m</td>
<td>229 sq m</td>
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<tr>
<td>8</td>
<td>Ratio of Wall area to floor area</td>
<td>0.61</td>
<td>0.43</td>
</tr>
<tr>
<td>9</td>
<td>Window to wall ratio, WWR (Area of windows/Area of exterior Wall)</td>
<td>(0.21) for N&amp;S, (0.19) for E&amp;W</td>
<td>(0.95) for N&amp;S, (0.42) For E&amp;W</td>
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<tr>
<td>10</td>
<td>Glass type of Window (Flat/Insulating...single pane, double pane, clear)</td>
<td>double glazed glass</td>
<td>single glazed glass</td>
</tr>
<tr>
<td></td>
<td>Shading Coefficient of window glass, SC</td>
<td>0.89</td>
<td>1</td>
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<td></td>
<td>Overall Coefficient or heat transfer value for Wall, Uw (W/m²)</td>
<td>0.295</td>
<td>0.295</td>
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<tr>
<td></td>
<td>Overall Coefficient or heat transfer value for glass, Ug (W/m²)</td>
<td>1.7</td>
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<td>11</td>
<td>Solar factor for North facing wall (W/m²), the average of solar factor in a year</td>
<td>49.67</td>
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<td>-----------------</td>
<td>---------------------------</td>
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<tr>
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<td>Correction factor for North facing wall</td>
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<td>Correction factor for West facing wall</td>
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<td>1.23</td>
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<td>Insulation inside the wall is A. Present B. Absent</td>
<td>Present</td>
<td>Present</td>
</tr>
<tr>
<td>13</td>
<td>If present, then name of the insulation materials</td>
<td>thick rigid insulation</td>
<td>thick rigid insulation</td>
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<tr>
<td>13</td>
<td>Insulation thickness for the entire opaque wall (mm)</td>
<td>50</td>
<td>50</td>
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<table>
<thead>
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<td>Type of Material used in roof</td>
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<td>Present</td>
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<td>If present, then name of the insulation material</td>
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<td>15</td>
<td>Insulation thickness for the entire opaque wall (mm)</td>
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<td>16</td>
<td>Lighting power density (LPD), (W/m²)</td>
<td>15 W/m²</td>
<td>21 W/m²</td>
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<td>17</td>
<td>Floor Area of conditioned space</td>
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<td>3300 m²</td>
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<td>17</td>
<td>Equipment power density (EPD) (W/m²)</td>
<td>35 W/m²</td>
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<td>Floor Area of conditioned space</td>
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<tr>
<td>17</td>
<td>Interior Temperature, Ti (deg C)</td>
<td>25.5</td>
<td>25.5</td>
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<td>18</td>
<td>Total operating hrs/week of the building</td>
<td>168 hrs/week</td>
<td>168 hrs/week</td>
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<tr>
<td>19</td>
<td>Total Electrical Energy Consumption per month (KWh) during summer (April-August)</td>
<td>700000 KWh</td>
<td>400000 KWh</td>
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<td>Total Cooling Requirement of Building, (TR)</td>
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<td>25</td>
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<td>20</td>
<td>Chiller Motor Input Power (KW)</td>
<td>&lt; 19 kw</td>
<td>66.44</td>
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<td>COP of Chiller</td>
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<td>Total Operating hrs/week of chiller</td>
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<td>168 hrs/week</td>
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<td>Type of Chiller : A. Split B. Central</td>
<td>Split</td>
<td>Chiller</td>
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<tr>
<td>21</td>
<td>Total Electrical Energy Consumption of chiller during summer (April-August), KWh</td>
<td>530000</td>
<td>310000</td>
</tr>
<tr>
<td>21</td>
<td>Monthly/Yearly electricity consumption by Chillers, (KWh/month, KWh/year)</td>
<td>70000 KWh/ month</td>
<td>40000 KWh/ month</td>
</tr>
</tbody>
</table>