DEVELOPMENT OF A SUSTAINABLE ENERGY RATING SYSTEM FOR RESIDENTIAL BUILDINGS IN SRI LANKA

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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ABSTRACT

Energy rating system can be considered as a key policy instrument that will assist the government to reduce energy consumption. Energy rating includes the direct benefits such as, energy requirement and carbon dioxide emission reduction, cost reduction for the users, increase the public awareness regarding energy issues, and improve the availability of information regarding the building. The government of Sri Lanka also has identified the importance of energy performance of buildings and considers it as a strategy for the sustainable energy development of the country. Existing rating systems in the world only considered limited factors related to energy consumption and to provide more accurate rating system it is proposed that a more sustainable energy rating system should be developed considering all the criteria. This research is aimed at identifying the existing rating systems, investigate the existing systems, to identify the parameters required for determining the energy performance of residential buildings, to develop and equation for calculating the energy score and to develop a scale for comparing the energy performance of residential buildings in hot and humid climate in Sri Lanka.

To achieve the above mentioned objectives, this research followed the concept of sustainable energy which comprises of both energy efficiency and renewable energy. The energy efficiency of a residential building needs to consider the energy efficiency due to building properties and energy efficiency of the occupants. To evaluate the energy efficiency of the building properties, the asset rating method was used where the building is modeled and the energy consumption for thermal comfort and lighting is calculated. Using 4569 different models (varying window to wall ratio, orientation, zone size, zone location, building shape and floor area), a parametric analysis was conducted to develop an optimum model which was then used as the reference value for the first sub rating (Building consumption rate). A questionnaire survey was conducted to identify the factors affecting the energy consumption of the Sri Lankan residential buildings and in total 336 filled questionnaires were used for parametric analysis. The questionnaire revealed that the number of bedrooms is not significant for energy consumption and the occupant characteristics and the equipment usage are highly significant factors. Therefore, when developing the occupancy behaviour rate, the average domestic energy consumption in Sri Lanka was used as reference, without normalising. To consider the renewable energy usage, another sub rating named energy source rate was developed and to decide whether to offset the energy consumption with renewable energy use or to use a separate index, another questionnaire survey was conducted with rooftop solar PV consumers. The results of the survey indicated that there is a strong rebound effect due to the solar PV adoption and there are some other social and technical impacts as well. Therefore, when developing the energy source rate, a sustainability index was used and based on the percentage of contribution of the energy sources to the final energy use the final energy source rate was determined.

These three sub ratings were normalised and brought to a common scale of 0 to 100. The sub ratings were integrated using weightages which were obtained using a perception survey of engineers, architects, quantity surveyors and facility managers in the industry. The application of the rating method is explained using two actual examples. Further, a sensitivity analysis was done to reflect the effect of the changes in the parameters used in the score calculation equation using the first sample house. The rating methodology proposed in this thesis can be used over any country or any building by changing the reference values and weightages.

Keywords: Energy rating; energy efficiency; buildings; thermal comfort; renewable energy; energy labels; consumer behaviour

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S. M. Pathirana

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BC_{rate}	Building Consumption Rate
CBA	Cost Benefit Analysis
ELECTRE	Elimination and Choice Translating Reality
ES_{rate}	Energy Source Rate
IRR	Internal Rate of Return
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LPD	Lighting Power Density
MAUT	Multi Attribute Utility Therory
MCDA	Multi Criteria Decision Aid
MIVES	Modelo Integrado de Valor para una Evaluacion Sostenible
NDCs	Nationally Determined Contributions
NPV	Net Present Value
OB_{rate}	Occupancy Behaviour Rate
PER	Primary Energy Ratio
PMV	Predicted Mean Vote
PPD	Predited Percentage Dissatisfied
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluation

SDGs	Sustainable Development Goals
SI	Sustainablity Index
SOS	System Of Systems
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
WWR	Window to Wall Ratio

CHAPTER 1

INTRODUCTION

Energy consumption in the world is rapidly increasing day by day mainly due to the population growth and the increase in the per capita energy consumption. The energy consumption increase is almost stagnated in OECD countries, however, in non-OECD countries the energy consumption increase is significant. The consumption increase can lead to various environmental and social issues as still a significant proportion of the electricity generation is done using non-renewable fossil fuel (figure 1.1).

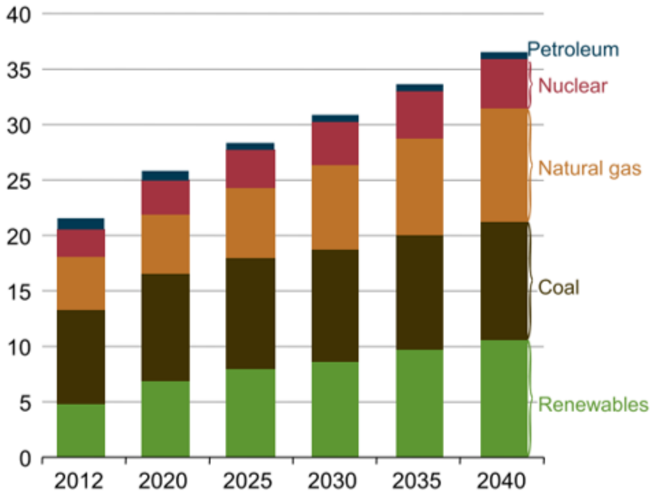


Figure 1.1: Net energy generation by energy source in the world (U.S Energy Information Administration, 2016)

The global climate change, depletion of fossil fuel and CO_2 emission increase have created a great interest in energy efficiency in various sectors including the construction industry. Energy represents a significant percentage of running cost of any building and also affects the thermal and optical comfort of the occupants. Energy efficiency is a key factor which is considered when purchasing many electronic and electrical equipment and the energy rating for those types of equipment are available to provide accurate information. Although the investment for buildings is considerably higher than most of those equipment, only developed countries and several developing countries have developed their own building energy ratings and certifications (Hinge, Cullen, Neely, & Taylor, 2014). However, the energy consumption in the building sector accounts for more than one fifth of annual energy consumption in the world and therefore ensuring energy efficiency in the building sector is utmost important. (U.S Energy Information Administration, 2016).

1.1 Energy performance assessment

In the assessment of energy performance, various levels of issues are addressed including environmental and energy. The objectives of the assessment are mainly providing the energy performance certification, energy decision making and energy performance diagnosis. These energy performance assessments can be conducted in to different level of details including, whole building level or multi level. The energy performance assessment systems can be further categorised to three main sections as energy performance diagnosis, building environmental assessment schemes and energy performance classification. The energy performance diagnosis is done at a system level and usually, a detailed energy audit is conducted. This is widely used for existing buildings and multi level assessment is carried out. The energy performance classification is performed at building level and this includes various systems including energy benchmarking, energy rating, energy labelling and energy certification. The building environmental assessment schemes consider all the environmental aspects in addition to the energy performance and in some of these systems the energy rating system obtained using energy performance classification is used to measure the energy performance. Some examples for the building environmental assessment schemes are LEED, CASBEE, BREEAM, and Green star. Figure 1.2 illustrates the categorisation of the energy performance assessment.

1.2 Energy rating systems

According to Stein and Meier (2000), energy rating system is defined as “a method which assesses the predicted energy use under standard conditions and the potential for improvement”. The energy rating provides an output with predicted energy use, a rating score which compares with a reference building and a list of recommendations for improving energy efficiency. Several examples of the energy rating systems in the world are Energy Star (USA), BEQ (USA), HERS (USA), MOHURD (China) and NatHERS (Austrailia)(Hinge et al., 2014). Most of the existing energy rating schemes are for new residential buildings since development and the application of the energy rating for existing buildings is difficult as a result of various socio-economic factors (Zmeureanu, Fazio, DePani, & Calla, 1999). However, the energy rating of buildings needs a method that can be applicable to both existing and new buildings while focusing on mainly the building features rather than their management.

Energy rating system can be considered as a key policy instrument that help regulatory bodies to reduce the energy consumption in the country. Energy rating includes the direct benefits such as, reduction of energy consumption and reduction of CO_2 emission; cost reduction for the users; increase the public awareness regarding energy issues and improve the available data for the building (International Energy Agency, 2010). The Sri Lankan government also has identified the importance of energy performance of buildings and considers energy rating as a strategy for the sustainable energy development of the country.

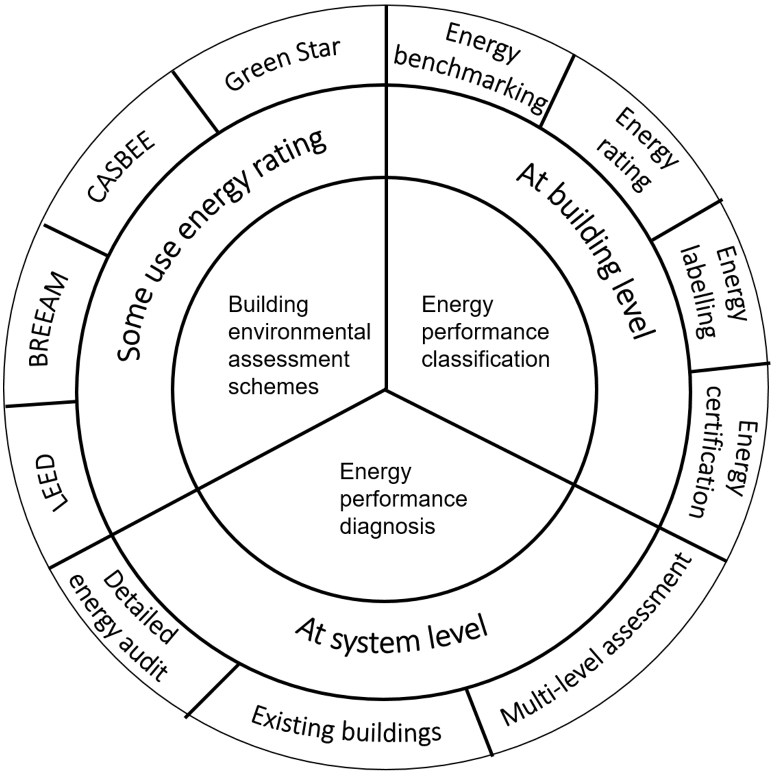


Figure 1.2: Energy performance assessment systems

Sri Lanka Sustainable Energy Authority prepared a code of practice to evaluate energy efficiency buildings in Sri Lanka and this code mainly covers the areas such as building envelop, lighting, ventilation and air conditioning, electrical power and distribution and service water heating (Sri Lanka Sustainable Energy Authority, 2009). Sri Lanka Sustainable Energy Authority has also identified that an energy rating system should be developed to check whether the buildings comply with the energy code.

However, when these energy rating systems are applied to an environment which is outside the scope, there are possibilities to arise inadequacies. Therefore, the existing energy rating systems are not used or applied across different climate zones and different countries (Wong, Lindsay, Crameri, & Holdsworth, 2015). Hence, the energy rating systems developed and used in other countries cannot be directly applied to Sri Lankan context. Although an energy rating system is specific to a country or climate, all the countries have the requirement to proceed with improving energy performance through policies. Hence, developing a building energy rating system that is tailored to the Sri Lankan culture and local climate is crucial for Sri Lanka.

The development and implementation of the energy rating systems would help the government to achieve the Sustainable Development Goals (SDGs) set by United Nations. The SDGs are as follows.

- No poverty
- Zero Hunger
- Good health and well being
- Quality education
- Gender equality
- Clean water and sanitation
- Affordable and clean energy
- Decent work and economic growth
- Industry, innovation and infrastructure
- Reducing inequality
- Sustainable cities and communities

- Responsible consumption and production
- Climate action
- Life below water
- Life on land
- Peace, justice and strong institution
- Partnerships for the goals

Energy rating systems enable the consumers to have an idea on their energy consumption and the responsible energy consumption behaviour. Further it encourage the renewable energy use while encouraging energy efficient building forms. The renewable energy sector development enable the clean energy goal and the responsible energy consumption behaviour results in responsible consumption. The energy efficiency and renewable energy will again promote the sustainable cities and communities while giving some room for taking the actions related to climate change. Furthermore, the energy rating systems would help the government to achieve the millennium development goals in Sri Lanka. Specially, it will ensure environmental sustainability and ensure sustainable development in Sri Lanka. This will further assist in achieving the Nationally Determined Contributions (NDCs) of Sri Lanka as well. There are seven NDCs of the energy sector which include the establishment of large scale wind power, solar power, biomass power and mini hydro power plants and introducing the demand side management activities, strengthening the sustainable energy and converting the fuel oil plants to LNG. Implementing the energy rating system will assist in archiving the demand side management NDC.

In Sri Lanka, the domestic energy consumption is significantly higher than the other sectors as illustrated in figure 1.3. Therefore, there is a significant requirement to have a policy to reduce the energy consumption at the domestic level and hence, this research is designed to target the residential buildings in Sri Lanka. The main aim of this research is developing an energy rating for Sri Lankan residential buildings in hot and humid climate. This will identify a common methodology which can be adapted to any country and any climate, however, the reference values and the weighage factors will be different based on the country and the climate. The characteristics of the building and consumption patterns will heavily defer according to the climate and the cultural differences.

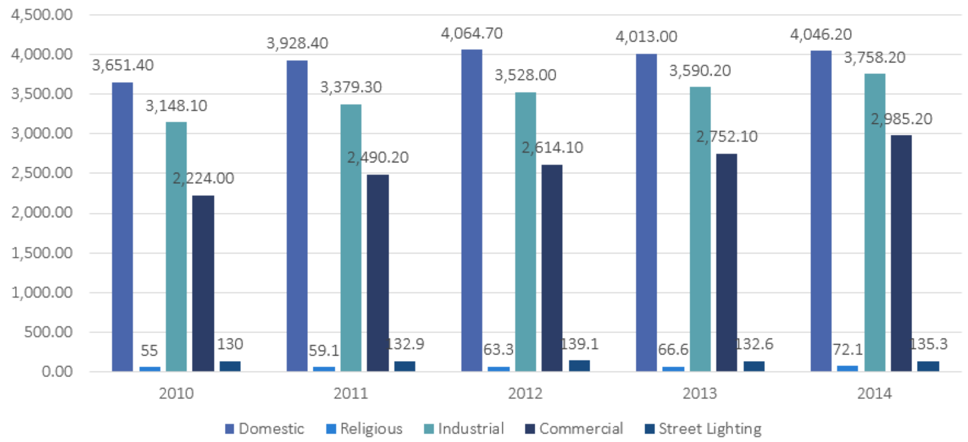


Figure 1.3: Electricity consumption of Sri Lanka by sector (SLSEA, 2018)

Therefore, an energy rating which is used by one country cannot be directly adapted to the Sri Lankan scenario. Further, the same reference values of energy rating cannot be used for all the climatic conditions in Sri Lanka as well. This research will provide a common guideline to develop an energy rating system which can be modified according to the climate, culture or the policy requirements.

1.3 Objectives

In order to achieve the above mentioned research requirement and research gap, this research was aimed at developing a sustainable energy rating methodology for residential buildings in Sri Lanka. The sub objectives of this research are as follows.

- To understand the existing rating systems and investigate the systems
- To identify the parameters required for determining the energy performance of residential buildings
- To develop an equation for calculating the energy score of residential buildings in hot and humid climate in Sri Lanka
- To develop a scale for comparing the energy performance of residential buildings in hot and humid climate in Sri Lanka

1.4 Scope

The overall model develop for the energy rating system could be applied to all the building types, any climate and for any policy situation. However, the case study application would be limited to the residential buildings in hot and humid climate in Sri Lanka. The residential buildings will include the single family detached buildings, multifamily buildings and apartment. In case of multifamily buildings and apartments the individual units will be assessed.

1.5 Methodology

Considering the inadequacies of the existing systems, this research developed a new energy rating methodology which is based on sustainable energy concept. In this concept, both energy efficiency and the renewable energy sources are considered and in energy efficiency, the energy consumed due to building characteristics and due to occupancy behaviour are considered. Three ratings were prepared to cover each aspect named; BC_{rate} for energy consumption due to building characteristics, OB_{rate} for energy consumption due to occupancy behaviour and ES_{rate} for the energy source. To develop BC_{rate} an optimum building was designed by analysing and conducting parametric study of 4569 models varying, orientation, window to wall ratios, zone locations, zone sizes, building shape etc. A questionnaire survey was conducted to obtain the reference values for the occupancy, lighting and other schedules. Further, this questionnaire reviewed that there is no significant correlation between the number of bedrooms and actual energy consumption and it rather governed by the equipment usage which is an significant occupancy factor. Therefore, for developing OB_{rate}, the average of energy consumption in Sri Lankan household was used. To develop the ES_{rate}, the sustainability index proposed by Cartelle Barros, Lara Coira, de la Cruz López, and del Caño Gochi (2015) was used. All these rates were then normalised to 0-100 scale and combined through weightage factors obtained through a questionnaire results which was based on the perception of the construction industry.

1.6 Main findings

This thesis provides a method to calculate the energy performance score of the residential building in tropical climate. The reference values for three bedroom, two story house in tropical climate was calculated and presented here. The equation which was derived to calculate the energy performance is as follows.
Energy rating score $= 0.36BC_{rate} + 0.32OB_{rate} + 0.32ES_{rate}$
Finally, a scale was developed to indicate the energy performance of the houses where, the score category 0-13 is defined as not energy efficient. Score category

14-32 is defined as the poor energy performance, 33-42 as below average energy performance, 43-61 as average energy performance, 62-70 as above average energy performance and 71-89 as good energy performance and 90-100 as best energy performance.

1.7 Structure and overview of the thesis

This thesis is structured in six main chapters.

Chapter 1 summarises the research background and the research problems and defines the objectives.

Chapter 2 serves as a review of literature which mainly discuss the energy rating systems in the world. The energy rating methodologies, the factors considered in energy rating and the scales used are discussed in detail. This chapter further discuss the factors affecting energy consumption including thermal comfort standards, building characteristics and occupants' behaviour. This further discuss the sustainable assessment of energy sources and multi criteria decision analysis.

Chapter 3 presents the research methodology which firstly discuss the research approach and then the methodologies used to develop optimum building, parametric analysis, consumer surveys and final score development.

Chapter 4 demonstrates the results of the model simulations, parametric analysis results, questionnaire survey results, sustainability assessment and analysis used for developing the final score.

Chapter 5 describes the application of energy rating system with an actual example and also discusses the policy implications.

Chapter 6 draws the conclusions about the key findings and provide recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The interest in the energy rating systems in buildings has been increasing over the past years mainly due to the impact of energy consumption of buildings to achieve the required optical and thermal comfort. This chapter will mainly discuss the existing energy rating systems giving special emphasis on the energy rating methodologies. The literature is further organised to provide more information on the thermal comfort standards, factors affecting the energy consumption of the buildings, sustainable energy assessment and multi criteria assessment which was then used in formulating the methodology.

2.2 Existing energy rating systems

In any building, energy is an important element as it represents a significant proportion of the operating cost of the building and it has a major impact on optical and thermal comfort of the occupant. The importance of energy efficiency in buildings arose in the early 1970s with the oil supply crisis (Laustsen, 2008) and emerged a requirement for the building energy rating as well. Over the past years, a large number of countries have developed and adopted various building energy rating systems. The current energy rating systems for buildings can be categorised into two, based on the assessment type as; calculated rating and measured rating (Sustainable Energy Authority of Ireland, 2015). The assessment methods that use the simulated or calculated energy consumptions is defined as asset rating or calculated rating. In this method, rather than the dynamic process of the building operations, the inherent energy performance properties of the building itself is considered (Leipziger, 2013). The energy consumption measure is based on a simulation model or a calculation tool such as AccuRate (Austrailia for NatHERS) (NatHERS National Administrator, 2012), HOT2000 (Canada for EnerGuide) (Natural Resources Canada, 2005), BREDEM (UK for SAP) (BRE, 2014), EnergimerkeKalkulator (Norway for Energimerking, and Ek-Pro (Denmark for Energimerker) Energistyrelsen (2014))(Isachsen, Grini, & Rode, 2010). If the calculation or modeling is conducted for a standard building conditions it is defined as the standard rating, and if it is for tailored conditions for a specific building, it is known as the tailored rating (Leipziger, 2013).

The measured rating is defined as the rating that is based on the actual energy consumption and is also known as operational rating. This rating is common in existing buildings and the energy consumption is measured using the utility meters. This is widely seen in residential buildings since the energy consumption figures are more sensitive to the behaviour of the occupants (Leipziger, 2013). To minimize the impact of the occupant aspects to the rating, the operational rating should be normalized for various conditions such as floor area and weather. BEE star rating system in India normalize the energy consumption for climate, hours of operation and the conditioned area (Seth, 2011). The Energy Star (USA) normalize energy consumption for weather (Energy Star, 2014) and the California HERS (USA) normalize for weather and number of billing days (California Energy Commission, 2010). Asset rating and operational rating provide different rating values and the only attempt made to combine these two was MOHURD system in China although it was not yet successful. In MOHURD system, only the asset rating should be displayed for the first year and after the first year, the operational rating is also given for one year, based on the continuous energy measurement. Here, the energy label displays both operational rating and asset rating after the first year (Mo et al., 2010).

2.2.1 Parameters used for existing energy rating systems.

When measuring and calculating energy use, the point at which point the energy should be measured should be considered. This would become a major requirement if the energy is obtained from different energy sources. Based on the point of measurement, the energy is classified into two as site energy and source energy. The energy value in utility bills normally falls in to site energy category and this bill value can be from primary energy (raw fuel burnt onsite such as fuel oil or natural gas) or secondary energy (energy product created from a raw fuel that is purchased through main grid) (Energy Star, n.d.). In most of the cases for energy rating the source energy is recommended, as it determines energy consumption of the building more accurately. The source energy cannot be measured directly, and therefore, the energy rating systems use conversion factors to convert site energy to source energy. Energy Star (Agency, 2014) and Building Energy Quotient (ASHRAE, n.d.) are some examples of the rating systems which use source energy and for a rating system which use site energy, Energimerking (Norway) (Enova SF, n.d.) can be taken as an example.

If the rating system use source energy, the fuel type is considered and hence usage of renewable energy is also concerned, especially when net zero energy is the main aim of the energy rating (ASHRAE, n.d.). In Energimerking (Norway) two grades are displayed in label as energy grade and heating grade, and the proportion of the renewable energy used in the building is reflected by the colour in the heating grade (Enova SF, n.d.). Although the carbon dioxide emission has not been considered in determining the energy rating, it is measured or calculated by several systems. The SAP system (UK) has indicated environmental (CO_2) impact rating and energy efficiency rating as two ratings in the energy label (BRE, 2014). Several energy ratings such as RESNET HERS (USA) considers the net zero energy home has zero carbon foot print and the scale is defined accordingly (RESNET, 2016).

Energy rating systems strictly consider the building's geographical location as many conditions such as climate and weather, depending on the location. The energy consumption applicable to hot climate will be different to cold climate due to the thermal energy requirement difference. When energy performance estimation is done through simulations, a weather file need to be given (Natural Resources Canada, 2005) which include data such as dry bulb temperature, daily temperature range, wind speed, wind direction and humidity. For operational rating, the energy consumption is normalized for weather.

The systems which use calculated rating (SAP (BRE, 2014), NatHers (NatHERS National Administrator, 2012), bEQ ASHRAE (n.d.), Energimerkng (Energistyrelsen, 2014)) usually use the physical characteristics of the buildings in their energy consumption calculations. The main reason for this is asset rating considers the inherent energy performance properties of the building. The properties of the building, such as building components (External walls, roofs, foundation, internal wall etc.), conditioned and unconditioned space, shape of the building, shading, orientation of the building, number of buildings (if an apartment complex), floor plan, building dimensions, construction type of the components and thermal performance of the components are widely considered in the calculations (Ballarini & Corrado, 2009). In addition mechanical ventilation, the ventilation and infiltration rates, heating and cooling degree days, HVAC systems and the heating or cooling system efficiencies are regarded in many energy rating systems (Chua & Chou, 2010; Williamson, Soebarto, Bennetts, & Radford, 2006). Except for few energy rating systems such as Mexico's PBE Edifica (Morishita et al., 2013), the passive houses and the natural ventilation have been ignored.

There are several parameters affecting the energy consumption of the building along with the above factors, such as plug and process loads and building specific scheduling which heavily depend on the occupant behaviour (Daniel, Soebarto, & Williamson, 2015; Klein et al., 2012; Masoso & Grobler, 2010). These energy uses heavily depend on the occupant aspects and in operational rating they are always considered. When calculating the energy consumption, some building energy modelling softwares ignore the plug and process loads and some systems (RESNET HERS) use projected energy use those loads (Leipziger, 2013).

2.2.2 Comparability matrix

The commonly used scales in the existing energy labelling systems can be categorised as continuous scale and discrete scales. The continuous scale place the rating value anywhere in the scale and the discrete scale, display a limited number of categories through set of letters or by stars (Leipziger, 2013). Rating systems such as Energimerking (A-G) (Energistyrelsen, 2014), BEE (5 star) (Seth, 2011), PBE Edifica (A G) (Morishita et al., 2013), NatHERS (10 stars)NatHERS National Administrator (2012) and MOHURD (5 star) (Mo et al., 2010) use discrete scales. Although discrete scales provide a better illustration, when rating the performance near the border of each category, the assessors usually meet with challenges. The systems such as EnerGuide (0-100) (Natural Resources Canada, 2005), BEQ (0-145) (ASHRAE, n.d.), and California HERS (0-250) (California Energy Commission, 2010) use continuous scales. These continuous scales differentiate best and worst energy performers better, although illustrating the comparative performance is difficult.

2.2.3 Existing energy rating methods

The current energy rating methods can be categorized to three main methods; calculated rating, measured rating and hybrid methods. The calculated rating can be further divided into two categories based on the method of quantification as; dynamic simulation and steady state method. In dynamic simulation, a detail simulation is carried out in order to capture building and system dynamics. The forward modeling is widely used in dynamic simulation where physical modeling is involved and simulation models such as HOT200, AccuRate and EnergyPlus are used by various existing rating systems. In steady state method, the dynamic effects are ignored and the calculation will be simplified by correlation factors. The inverse modelling techniques which use regression models are widely used in this steady state methods. The measured rating can be further categorized in to two as monitoring based and bill based methods. The monitoring based methods involve the end use sub metering and BMS based methods. The bill based methods use the final meter reading of the electricity or any other energy source and need a proper energy disaggregation method. The hybrid methods are mainly based on calculations, and measured data are used to reduce the calculation discrepancies.

2.2.4 Research gap

The existing systems are mainly falling into calculated rating (Dynamic simulation based) or the Measured rating (Bill based). Using only one rating method may not provide the true picture of the energy consumption scenario of the building, and thus there are several attempts to make hybrid methods. The existing MOHOURD system in China is one such attempt, which displays both rating in the same certificate without proper integration. The previous literature or the existing rating systems do not provide examples for a properly integrated hybrid method which include pros of both calculated and measured rating systems. Further, the existing rating systems are only representing only few aspects of the sustainable energy and hence does not provide an accurate picture about the sustainability of the energy use in the building. Therefore this research would try to fill the above gap by developing a rating based on hybrid method which can be altered easily based on the policy changes and can be modified easily for any country or climate.

2.3 Thermal comfort

Thermal comfort in a building is an essential key parameter to achieve a comfortable and healthy indoor environment (Djongyang, Tchinda, & Njomo, 2010). In the literature, various definitions are available for thermal comfort. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) has defined thermal comfort as “the condition of the mind in which satisfaction is expressed with the thermal environment”. Some other definitions are also available such as “a state in which there are no driving impulses to correct the environment by the behaviour” (Hensen, 1991) and simply stated, the occupants should feel neither cool nor warm in a thermally comfortable environment (Frontczak & Wargocki, 2011).

The ISO 7730 standard defined two indices to measure the thermal comfortability inside a building. The Predicted mean vote (PMV) index measures the mean thermal sensation and the predicted percentage dissatisfied (PPD) predict the mean satisfaction of the thermal condition of people. The standard further defines the thermal environment as a function of two people related variables (clothing and activity level) and four physical variables (humidity, air temperature, relative air velocity and mean radiant temperature) (Frontczak and Wargocki, 2011). These standards have been developed to define the acceptable ranges of the above variables and parameters. Meeting those standards does not does not imply that all the occupants in the building are satisfied with the thermal comfort inside the building. The main reason for this is the requirements and the nature of various people are difference and hence not all of them satisfy with same environmental conditions. The other reason is that in addition to the physical conditions there are other factors affecting the satisfaction with the indoor thermal comfort (Frontczak & Wargocki, 2011).

The thermal comfort standards define the thermal temperature ranges so that at least 80% of the occupants are satisfied with the thermal conditions (Djongyang et al., 2010). The thermal comfortability mainly depends on the heat exchange between the human body and the environment surrounded and therefore several studies have been carried out proposing adaptive approaches. These adaptive approaches assume that people can adapt to the environment through behavioral adjustments and relaxation of expectations (Frontczak & Wargocki, 2011). However, there is no absolute standard for determining the thermal comfort. In general, the thermal comfort occurs when the body temperature is maintained within lower ranges and low level of moisture (Djongyang et al., 2010). Furthermore, the thermal comfort determines the energy consumption of the building and therefore, it is important in achieving the sustainability of the building. The outdoor microclimate can contribute highly to the improvement in thermal comfort inside a building and therefore this can be efficiently used for achieving building energy efficiency. Also, the knowledge on the relative importance of the microclimatic conditions on the thermal comfort of the occupants is useful for design interventions and urban planning (Krüger & Rossi, 2011).

2.3.1 Factors affecting thermal comfort

According to several studies (Djongyang et al., 2010; Frontczak & Wargocki, 2011) the thermal comfort is affected by six factors, including four physical variables (air velocity, relative humidity, air temperature and mean radiant temperature) and two personal variables (activity level and clothing insulation). However, in addition to those physical and personal variables, other factors such as the building type, adaptations and psychological factors can affect thermal comfort.

2.3.1.1 Type of building

The building type has a great influence on the thermal comfortability inside a building. The thermal comfort requirement varies when the building type is different such as home, office or other commercial establishments. Also when the building is naturally ventilated, the level of thermal comfort requirement differ than when it is air conditioned (Frontczak & Wargocki, 2011). According to this study, the people often feel warmer at home and have colder sensation in office. Also the neutral temperatures differ based on the type of the building. This difference in the neutral temperature can be explained partially by the other environmental parameters such as air velocity, activity level, clothing insulation and humidity. The users of the natural ventilated buildings have lesser expectations regarding the indoor thermal comfort compared to the users of air conditioned buildings. These natural ventilated building users accept lower temperatures in winter and higher indoor temperatures in summer. Moreover, these occupants accept wider temperature ranges (Frontczak & Wargocki, 2011). In countries such as Thailand, Israel, Singapore and southern part of China which have warm climates, the neutral temperatures and comfort temperatures the occupants feel in warm seasons are higher in natural ventilated buildings compared to the air conditioned buildings in all building types.

2.3.1.2 Adaptation

Adaptation can be defined broadly as “the gradual decrease of the organisms response to repeated exposure to a stimulus, involving all the actions that make them better suited to survive in such an environment” (Nikolopoulou & Steemers, 2003). When relating the adaptation to the thermal comfort, it involves all the processes which the occupants follow in order to improve the fit between the indoor environment and the occupant requirements. These adaptation conditions fall mainly into three categories as physical adaptation, physiological adaptation and psychological adaptation (Nikolopoulou & Steemers, 2003).

The physical adaptation includes all the changes that a particular person makes for adjusting to the environment or to change the environment according to his requirements. Based on that it is possible to identify two categories of physical adaptation, reactive and interactive. In reactive adaptation, only the personal changes occur, such as altering the clothing levels, position and posture, change in metabolic heat by consuming hot or cool beverage etc. However in interactive adaptation, the environment is changed by people to improve the thermal comfort to their requirement and that may involve activities such as opening a window or turning a thermostat (Nikolopoulou & Steemers, 2003).

The physiological adaptation involves the changes in the physiological responses which result due to repeated exposure to some factor which leads to gradual decrease in strain from that exposure. The psychological adaptation is now considered as increasingly important although it cannot be measured by physical parameters, as they result in wide fluctuations in the physical environment in order to avoid the thermal discomfort. There are several issues related to psychological adaptation including; naturalness, expectations, experience, environmental stimulation, perceived control and time of exposure (Nikolopoulou & Steemers, 2003). Naturalness explains that in a natural environment the people can tolerate wide changes to physical environment if those changes are produced naturally. The peoples expectation on the environment has a great influence on the occupants perceptions rather than the actual environment. This is mostly evident in case of naturally ventilated buildings as the people expect temperature variations. In air conditioned buildings the people expect more stable thermal environment. These kinds of expectations of the people also depend on the experience which can be differentiated in long term and short term. Short term experience are memory related and can change the expectation of the people from one day to another (Nikolopoulou & Steemers, 2003).

2.3.1.3 Other factors

The perception of thermal comfort depends on the gender and therefore women and men feel the thermal comfort level differently. Also it depends on whether this environment is the home or the workplace of the person and also whether he is a visitor or occupant. Also, it depends on the position of the workstation from the window and the duration of the stay inside that building. The perception on the thermal comfort differs across different countries and depend on whether the building is public or private (Frontczak & Wargocki, 2011). In addition to that, thermal comfort depends on various behavioural actions including altering activity, altering clothing, changing thermostat setting, changing posture or location, opening a window or leaving a space etc. (Djongyang et al., 2010).

2.3.2 Thermal comfort standards in built environment

Various thermal comfort standards are available in the literature and in this section the ISO 7730 standard and the ASHRAE 55 standards are discussed.

2.3.2.1 ISO 7730 - Thermal comfort standard

By introducing Fanger steady state model, in 1984 ISO 7730 was first presented as a comfort standard. This standard included the methods to calculate the thermal comfort indices of Fanger (PMV and PPD) and to assess the discomfort caused by radiation, difference in vertical air temperature, and draught. The standard was last revised in 2005 by introducing different comfort categories for various levels of PPD. However, this model does not discuss the adaptive comfort theories.

2.3.2.2 ASHRAE 55 standard - Adaptive thermal comfort

This ASHARE 55 adaptive comfort standard was firstly introduced in 1966 and most recently revised in 2017. Although this is not an international standard, this model is considered as a global implementation of this adaptive comfort concept. In ASHARE 55: 2017 version, the acceptable levels of operative temperature ranges are in two categories; named 80% acceptability and 90% acceptability (ASHRAE, 2017). To apply the adaptive comfort model, the building should satisfy the following conditions.

- Only applied to occupant controlled naturally ventilated and conditioned buildings
- Mechanical cooling systems are not installed
- No heating systems are installed
- Metabolic rates of occupants are between 1.0 to 1.3 met

- Occupants can adapt the clothing freely based on the thermal conditions indoor or outdoor
- Prevailing mean outdoor temperature should be more than 10^0C and less than 33.5^0C.

If the prevailing outdoor temperature is not within the 10^0C to 33.5^0C range, then a mechanical cooling or heating system should be installed and the set points should be determined by Fanger model (ASHRAE, 2017). The temperature ranges related to different acceptability levels are shown in figure 2.1.

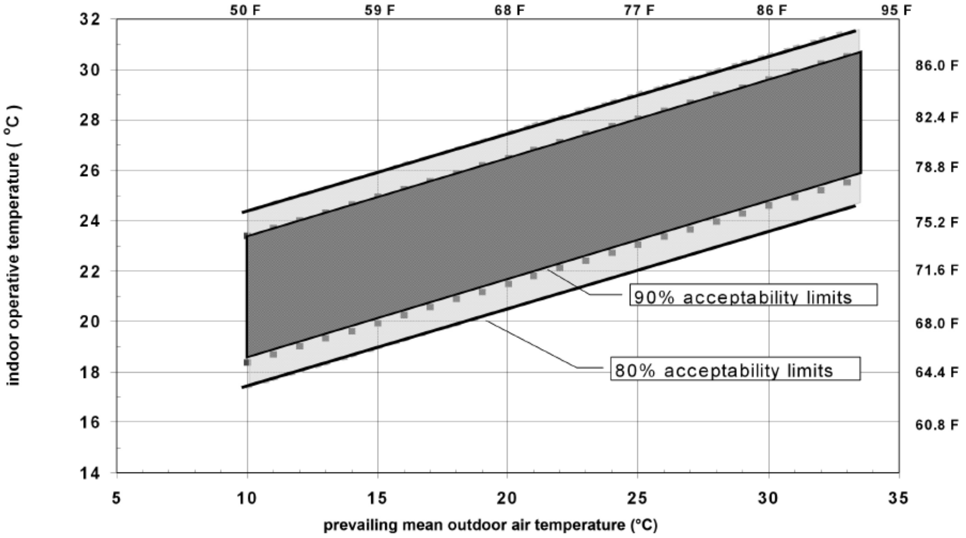


Figure 2.1: Acceptable operative temperature ranges in ASHRAE 55 (2017) in naturally conditioned spaces (ASHRAE, 2017)

The upper and lower acceptability limits for operative temperatures can be calculated using the equation 2.1 (ASHRAE, 2017; Carlucci, Bai, de Dear, & Yang, 2018).

$$\begin{aligned}\text{Upper 80\% acceptability limit } (^0C) &= 0.31\overline{t_{pma(out)}} + 21.3\\ \text{Upper 90\% acceptability limit } (^0C) &= 0.31\overline{t_{pma(out)}} + 20.3\\ \text{Lower 80\% acceptability limit } (^0C) &= 0.31\overline{t_{pma(out)}} + 14.3\\ \text{Lower 90\% acceptability limit } (^0C) &= 0.31\overline{t_{pma(out)}} + 15.3\end{aligned} \tag{2.1}$$

2.4 Effect of building form on the energy efficiency

Higher energy cost, poor indoor air quality and the environmental impact of energy generation have made higher interest in natural ventilation compared to air conditioning and heating, in the recent literature. The higher humidity level and intensive solar ration in hot humid region require the buildings to use air conditioning which causes higher electricity consumption. L. Wang, Nyuk, and Li (2007). Achieving the required thermal comfort levels without mechanical cooling systems is difficult for most tropical countries and the issue is becoming worse due to global warming. In air conditioned buildings, the required thermal comfort levels can be easily achieved through higher electricity consumption. However, in poorly designed buildings with only natural ventilation, the thermal comfort levels cannot be controlled.

To identify the effect of building shape or building form on energy load, various attempts have been made. Through a simplified analysis method, Ourghi, Al-Anzi, and Krarti (2007) predicted the impact of the building shape on total energy use and annual cooling load in an air-conditioned office building. The model was simulated for four locations (Tunis, Rome, Cairo and Gabes) and the result showed that there is a strong interdependence between building energy load and basic features of the building such as window size, glazing type and budding shape. Using evolutionary algorithm, Caruso and Kämpf (2015) analysed the optimal building form (three dimensional form) which minimise air conditioning energy needs and identified that the optimal forms are compact and follows a self shading concept while orienting to a certain direction which depends on the site. Further, the heating load is directly proportional to shape coefficient in cold climate (Depecker, Menezo, Virgone, & Lepers, 2001). The shape coefficient is defined as follows (Depecker et al., 2001).

$$C_f = \frac{S_e}{V} \tag{2.2}$$

Where, S_e is surface area of envelop and V is the building inner volume. However, the study of Depecker et al. (2001) has largely ignored the parameters such as WWR, orientation and climate and only focused on the shape of the building.

Conversely, using an air-conditioned office buildings in Kuwait, AlAnzi, Seo, and Krarti (2009) presented an analysis method that evaluate the effect of building shape on energy efficiency. During the analysis various building forms and shapes have been considered which includes rectangular, U shaped, L shaped, cross shaped, T shaped, cut shaped and H shaped. The results indicated that, the total energy use is inversely proportional to the relative compactness of buildings with low WWR, irrespective its building form.

Alwetaishi (2017) studied the impact of orientation and WWR on the energy load of educational buildings in different climates and the optimal WWR was found to be 10% for hot and humid region. Using a study in Teheran, Gomez-Mejia, Luis and Balkin (2007) identified that by properly selecting the building orientation it is possible to save the annual building energy consumption up to 105% and when deciding the building orientation a special focus should be made on the WWR. Therefore, studying the effect of orientation and WWR on energy efficiency is vital in analysing the connection between energy use and building shape.

For cold climates, similar researches have been conducted focusing on heating load. Oral and Yilmaz (2002, 2003) developed a method to determine the building form that contributes to minimum heat load. For multistory office buildings in Australia, Marks (1997) investigated the glazing parameters, optimum wall length proportions and the angles and this was further extended by Jedrzejuk and Marks (2002) and developed a muliti-criteria optimisation method of the building shape, structure and heat source. Further, using a simulation study, Mangkuto, Rohmah, and Asri (2016) investigated the effect of window orientation, wall reflectance and WWR on daylight metrics and lighting energy demand, for the buildings in tropical climate. According to the pareto optimisation, the optimum solution received as wall reflectance is 0.8, WWR is 30% and south orientation.

The studies discussed above are mainly focused on non-residential buildings like office buildings that depends heavily on cooling and heating. However, the effect of building form on energy consumption of residential buildings should be studied separately as the occupancy patterns in the residential buildings are different to non-residential buildings and the daytime energy use is lower. Several researches have been conducted to determine the effect of WWR, orientation and building shape in residential buildings. In non-convex shapes, as per a research conducted by Hachem, Athienitis, and Fazio (2011), the solar radiation is significantly affected by the ratio between the shading to shaded facade and the number of shading facades. This study was based on residential buildings in cold climate and Hachem et al. (2011) considered seven different shapes (rectangle, square, trapezoid, U, L, T and H) for the analysis. For single family houses in five different locations in the United States, Bichiou and Krarti (2011) conducted a research while taking WWR, orientation and building shape as important parameters for the optimisation. Bichiou and Krarti (2011) considered three optimisation algorithms and derived an optimum design which reduced the cost by 10-25 % depending on the climate and type of house.

L. Wang et al. (2007) investigated the optimum thermal comfort of naturally ventilated residential buildings by changing WWR, orientations, U-values and lengths of shading device. This research was focused on a typical residential building in Singapore and it was found that, U-value of facade materials should be less than 2.5 W/m^2K and the optimum WWR is 24%. Mirrahimi et al. (2016) considered the effect of building form on the energy consumption in tropical climate in Malaysia and the factors such as natural ventilation, external walls, glazing area and roofs were the main factors that were evaluated. However, the above two researches were not focused on either lighting electricity or zones.

As previously discussed most of the above studies are restricted to air conditioned buildings and the studies with natural ventilation considers only the buildings with one zone (Bambrook, Sproul, & Jacob, 2011). Therefore, for the residential buildings in the hot humid climate, the knowledge on the effect of building form and the zones on the naturally ventilated buildings is rare. Bre, Silva, Ghisi, and Fachinotti (2016) optimised a typical residential building in Argentina where part of the rooms were air conditioned and others were naturally ventilated. The results indicated that, thermal transmittance and solar absorptans of external walls, WWR and orientation are important factors when reducing the cooling energy demand.

The previous studies have not sufficiently covered the effect of building shape, orientation, WWR and zones in residential buildings in tropical climate. Also, in the available few studies on residential buildings in hot and humid climate, the effect of zone sizes and zone locations have not been discussed. Moreover, in most of studies related to residential buildings, the lighting electricity requirement is heavily neglected and only the total energy demand has been considered. For naturally ventilated buildings it is important to identify the effect of lighting energy separately due to the contribution of the building elements on artificial lighting requirements.

2.5 Effect of occupant behaviour on energy consumption

Energy conservation in household has gained significant attention in various social and environmental related research for a number of decades. Due to various macro level factors as listed below, the household energy consumption is increasing (Gatersleben & Vlek, 1998).

- Technology development (eg. energy intensive equipments and appliances)
- Institutional factors (eg. government policies)
- demographic factors (eg. population growth)
- Economic growth (eg. increase in household income)
- Cultural developments (eg. increasing the number of employed women in household)

Energy efficiency related occupant behaviours are falling in to two different categories as efficiency behaviours (one time efforts such as purchasing energy efficiency devices and insulating the houses) and curtailment behaviours (repetitive efforts such as changing the thermostat settings) (Gardner & Stern, 2002). The energy efficiency behaviours have higher impact on saving energy rather than thermostat settings (Gardner & Stern, 2002). However, the effect of the energy efficiency behaviours can be reduced due to rebound effect. For example, the energy saving due to energy efficient devices will be reduced if the device is used more frequently (Berkhout, Muskens, & W. Velthuijsen, 2000). The household energy consumption is dynamic and changes with time of the day and also with the season (day of the year).The components of household energy consumption can be classified in to three main categories as follows (Wood & Newborough, 2002).

- *Predictable* – When building is unoccupied or occupants do not control the devices (eg. refrigerators, security lighting, devices on standby)
- *Moderately predictable* – consumptions related to habitual or regular behaviour patterns of the occupants (eg. watching television programs, switching on or off the lights on week days when the occupant get up and leave home for work)
- *Unpredictable* – consumptions related to irregular behaviour patterns of the occupants (eg. cooking, washing or drying)

Although these consumption categories are evident in majority of the households, it is difficult to explain the difference of the energy consumption of similar households. Studies in various countries (Unites States, UK and Netherland) have estimated that a considerable percentage (26% to 36%) of the home energy use occurs due to occupant behaviour (Mansouri-Azar, Newborough, & Probert, 1996; Sonderegger, 1978; Verhallen & Van Raaij, 1981). Another study in UK reviled that the electricity consumption increase by 10% due to the standby appliances and 5% due to the active appliances (Firth, Lomas, Wright, & Wall, 2008). Therefore, the change in energy consumption pattern can be an effective way to reduce the energy consumption of the households. Also, by providing more information on the energy consumption and the reduction potential it is easy to create the consumer awareness and reduce the consumption. However, to modify the behavioural patterns of the consumers, a complex interaction of both social and technical phenomena should be there (Hitchcock, 1993; Mansouri-Azar et al., 1996).

Energy consumption behaviour of the occupants plays an important role in the determination of the domestic energy consumption pattern and the magnitude of energy use. Considering the importance of the energy use behaviour, numerous researches in various disciplines, including social policy and environmental psychology have conducted researches in this regard (Abrahamse & Steg, 2009; Abrahamse, Steg, Vlek, & Rothengatter, 2005; Carrico, Vandenbergh, Stern, & Gardner, 2011; Dietz, 2010; Poortinga, Steg, Vlek, & Wiersma, 2003; Steg, 2008; Steg, Dreijerink, & Abrahamse, 2005; Stern, Gardner, Vandenbergh, Dietz, & Gilligan, 2010).

Hitchcock (1993) provided another method of categorising the energy consumption behaviour of the occupants as follows.

- *Usage related*- - Day to day usage frequency, duration of use and intensity of the device or equipment
- *Maintenance related* – Service or repair the appliances and heating or cooling equipments in household
- *Purchase related* – Energy attributes of the products selected by the occupants (eg. energy efficient appliances or thermal insulation of the house etc.)

Number of studies have discussed on the other factors that govern the annual energy consumption of household that may be directly or indirectly related to the consumer conditions and the behaviour. According to a study conducted by Yohanis, MOndol, Wright, and Norton (2008) there is a strong correlation between floor area and the energy consumption, mainly due to the higher heating energy requirement in the winter for large floor areas. Druckman and Jackson (2008) found that the type of the house, household composition, tenure and location affect the energy consumption of the household. Further, several studies have investigated the impact of household income for the energy consumption (Kerkhof, Benders, & Moll, 2009; Summerfield et al., 2007; Wall & Crosbie, 2009) and although income is an important factor affecting the energy consumption, the relationship between the income and energy consumption is much complex due to the effect of other important factors such as education levels and awareness of the occupants.

Factors that influence the occupants' behaviour on energy usage can be further divided in to three domains according to the discipline (Building science, economic or social science). In building sciences, mostly the physical parameters such as the outdoor air temperature, solar radiation and the indoor air temperature are considered. These parameters affect the behaviours such as window opening. However, there can be other forms of parameters that can affect such window opening behaviours such as; physical and biological conditions of the occupants, phycological conditions and interactions between the occupants, economy of the household and culture) (Andersen, Toftum, Andersen, & Olesen, 2009).

2.6 Sustainability assessment of energy sources

Sustainability assessment can be considered as a logical assessment of environmental assessment, although the latter is generally program or project specific and the sustainabile assessment consider the integration of all the aspects of sustainability (environmental, social and economic) (Gibson, 2001),

Several past studies on the sustainability assessment of energy sources are based on the principle criteria for sustainability assessment by Gibson (2001) which are listed in table 2.1.

Table 2.1: Principle criteria for sustainability assessment

Criteria	Requirement
Socio-ecological system integrity	Creating human - ecological relations to maintain integrity of Socio-biophysical systems in long term
Livelihood sufficiency and opportunity	Everyone has enough for decent life and opportunities for improvements
Intragenerational equity	Reduce the gaps in sufficiency and opportunity between rich and poor though effective choices
Intergenerational equity	Preserve and enhance the opportunities and capabilities for the sustainable livelihood of future generation
Resource maintainable and efficiency	Providing a base for sustainable livelihood for everybody by minimising the threat to the socio-ecological system integrity
Democratic governance and socio-ecological civility	Build the capability of the decision making bodies to apply requirements of the sustainability
Precaution and adaptation	Respect uncertainty and avoid the damage to sustainability
Immediate and long term integration	Apply all the principles of sustainability

Rosenthal (2004) presented a procedure for sustainable assessment of energy sources which consider both qualitative and quantitative data from three main categories.

- *Electricity infrastructure* – Local air, water, soil pollution related to electricity production
- *System regulations* – Environmental standards and air quality reporting
- *Attitude of local residents* – Response regarding air quality and awareness of local production methods

Rosenthal (2004) categorised these items according to the sustainability principles presented in (Gibson, 2001) and the potential indicators for sustainability assessment of energy sources by Rosenthal (2004) is available in table 2.2.

Table 2.2: Sustainability principles and sustainability assessment indicators (Rosenthal, 2004)

Sustainability principle	Potential indicators
Socio-ecological system integrity	• SO_2 emissions per capita and per GWh • CO_2 emissions per capita and per GWh • Air pollution index
Livelihood sufficiency and opportunity	• Production to consumption ratio • Electricity system performance indices
Intragenerational equity	• Per capita consumption levels of urban and rural residents • Distribution of electricity consumption figures across the population • Percentage of household income spent on electricity
Intergenerational equity	
Resource maintainable and efficiency	• Industrial electricity consumption per GDP • Total electricity consumption per GDP and per capita • Power plant utilization rate • Transmission and distribution losses
Democratic governance and socio-ecological civility	• Electricity portfolio • Strategies for cleaner production • Number of opportunities for public to provide inputs for electricity related projects
Precaution and adaptation	• Number of environmental assessments and sustainable energy assessments completed for electricity sector

A similar study has been conducted by Gaudreau (2013) on the sustainability assessment of various energy sources and have used the Gibson's approach (Gibson, 2006) to assess various energy sources in several countries. To facilitate the decision making on the renewable energy sources, Polatidis, Haralambopoulos, Munda, and Vreeker (2006) developed a methodology using multi criteria decision analysis which includes seven main categories. This includes all the sustainability related factors such as environmental benefits and impacts, social impacts and economic aspects as shown in figure 2.2.

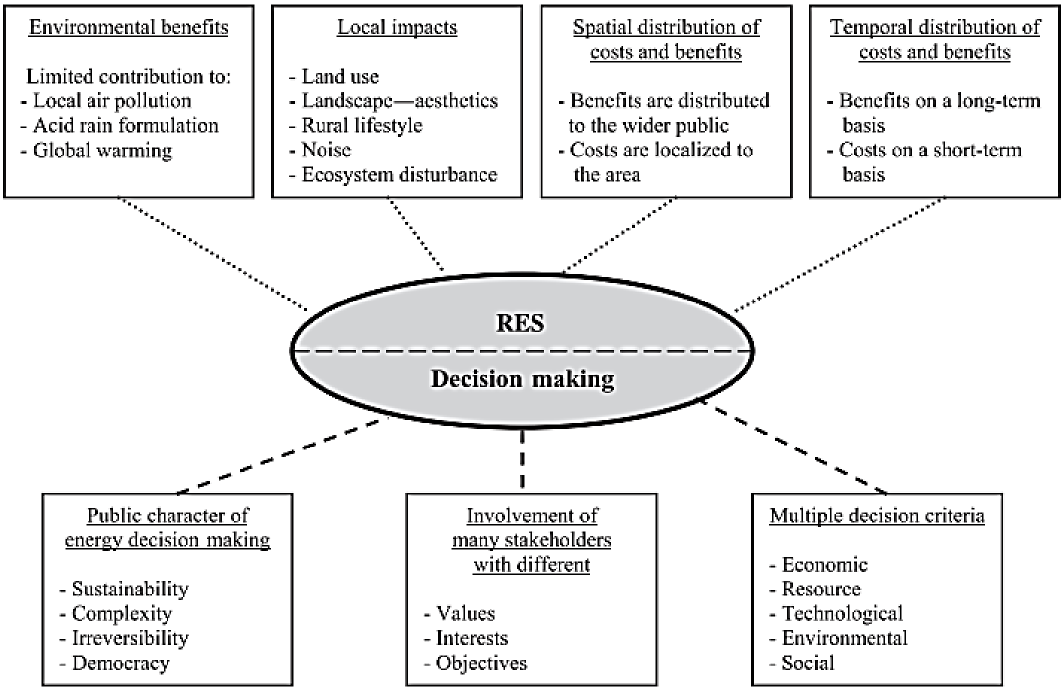


Figure 2.2: Renewable energy sources: decision making (Polatidis et al., 2006)

Hadian and Madani (2015) introduced a different method for energy sustainability assessment which is named as system of systems (SOS) framework. This framework considers four different aspects; water, economy, land and climate and these were measured in terms of Carbon footprint (g CO_2/kWh), water footprint (m^2/GJ), land footprint (m^2/GWh)and Cost (cents/kWh). Numerous other researches have been carried out taking the main categories of sustainability (environmental, social, economic) as the basis for sustainability assessment. For example, Al Garni, Kassem, Awasthi, Komljenovic, and Al-Haddad (2016) extended these main sustainability categories to four different criteria by adding technical to other three criterion. The sub criteria related to each main criteria are presented in table 2.3.

Table 2.3: Sustainable energy technologies and assessment (Al Garni et al., 2016)

Criteria	Sub criteria
Technical	• Resource availability • Ease of decentralisation • Efficiency • Technology maturity • Energy system safety
Environmental	• Land requirement • Impact on emission level
Socio-political	• Job creation • Maintaining energy leading position • Socio-political acceptance
Economic	• Capital cost • National economic development • Operations and maintainable cost • Energy cost

Santoyo-Castelazo and Azapagic (2014) has directly adapted the three aspects of sustainability to their model and prepared a methodology including three assessment scenarios; environmental assessment, economic assessment and social assessment. For the environmental assessment, a life cycle approach has been taken and ten impacts including global warming, resource depletion, acidification, eutrophication, freshwater toxicity, human toxicity, marine toxicity, ozone depletion, summer smog and terrestrial toxicity were considered. As economic indicators, capital costs, total annualised costs and levelised costs have been taken. As social indicators, security and diversity of supply, public acceptance, health and safety and intergenerational issues have been considered.

By reviewing 183 research articles, Strantzali and Aravossis (2016) classified the sustainability assessment criteria as technical, economic, environmental and social criteria. Under each criteria, the main aspects covered were recorded and the percentage of papers appeared under the particular aspect were counted as indicated in table 2.4.

Table 2.4: Classification of sustainability assessment criteria (Strantzali & Aravossis, 2016)

Technical criteria	%
Efficiency	31%
Reliability	20%
Resource availability	18%
Nominal power/Installed capacity (kW)	17%
Maturity	16%
Safety	10%
Energy production	9%
Demand	9%
Primary Energy Ratio (PER)	8%
Lifespan	8%
Continuity	5%
Stability	3%
Economic criteria	%
Investment Cost	52%
Operation and Maintenance Cost	34%
Energy cost	23%
Payback period	16%
Internal Rate of Return (IRR)	9%
Life Cycle Cost (LCC)	6%
Net Present Value (NPV)	5%
Service life	5%
Equivalent Annual Cost (EAC)	2%
Environmental criteria	%
CO2 emissions	52%
Land use	33%
Impacts on ecosystems	31%
NOx emissions	22%
SO2 emissions	17%
Emissions (generally)	17%
Noise	14%
Particles emissions	2%
Social criteria	%
Job creation	46%
Social acceptability	28%
Social benefits	15%
Visual impact	14%
Local development	13%
Impacts on health	10%
Income from jobs	8%

2.6.1 Decision support methods for energy sources

The decision support methods for energy sources are mainly in three categories as; life cycle analysis (LCA), cost benefit analysis (CBA) and multi criteria decision aid (MCDA)(Shmelev, 2012).

2.6.1.1 Life cycle analysis (LCA)

Life cycle analysis is defined as "a process that analyse and assess the total environmental impact over a whole life cycle of a product, activity or a process". In LCA, all the energy and material uses and the released waste to environment are identified and quantified. The entire life cycle which is considered in LCA are the extracting and processing the raw materials, manufacturing, transportation, distribution, use, maintenance, re-use, recycle and disposal of the product (Benoit & Mazijn, 2009).

According to a review conducted by Lund and Biswas (2008), LCA is conducted with various objectives in electricity generation from renewable energy technologies as shown below.

- To determine environmental performance
- To analyse the factors of environmental performance
- To conduct scenario analysis
- To conduct comparative analysis of different energy sources

2.6.1.2 Cost benefit analysis (CBA)

Cost benefit analysis is an alternative method to determine the performance by translating all the impacts to monetary terms. The CBA compares total costs in a particular project or policy. The costs and benefits can be private costs (market prices) or external costs (external economic and natural environment). This will facilitate the selection of the actions that will lower the social cost and maximise the net social benefits. However, it is difficult to use this in all the cases, as not all the impacts can be converted to monetary terms (Lund & Biswas, 2008). However, these monetary values available in CBA can be used as weitages in multi criteria decision aid (Hammond, 1966).

2.6.1.3 Multicriteria decision aid (MCDA)

In sustainable energy assessment, multicriteria decsion aid (MCDA) is widely used as it can provide effective solutions to multiple and conflicting objectives. In energy decision making various MCDA including weighted averages, outranking, priority setting, fuzzy principles and combinations of those methods are widely used. MCDA is widely used in analysing energy policy, power planning, project appraisal, selecting technologies and environmental impact analysis (Zhou, Ang, & Poh, 2006). In section 2.7, the techniques that are used for MCDA are widely discussed.

2.7 Multi criteria decision analysis

Multi criteria decision aid or multi criteria decision analysis (MCDA) is a widely used method in decision making. Various types of MCDA methods are available including weighted sum method, analytic hierarchy process (AHP) or analytic network process (ANP), the technique for order preference by similarity to ideal solutions (TOPSIS), multi attribute utility theory (MAUT), MCDA combined fuzzy methods, and outranking methods (ELECTRE and PROMETHEE) (Strantzali & Aravossis, 2016).

2.7.1 Weighted sum method

The weighted average method is the most simplest and widely used techniques among the multi criteria decision analysis. This is based on the weighted average where, the evaluation score is calculated by multiplying the scaled value with the weightage assigned for attributes in each alternative. The sum is the index and it is used for the purpose of evaluation of each alternative. The best alternative can be obtained using the equation 2.3. However, when different dimensions are involved, it is difficult to use this weighted average methods as the additive utility assumption will be violated by the different units (Sólnes, 2003).

$$A^*_{WSM} = Max \sum_{i}^{j} a_{ij} w_j \tag{2.3}$$

For i = 1,2,3,....M
Where;
A^*_{WSM} = Score of the best alternative
a_{ij} = Actual value of the i^{th} alternative in terms of j^{th} criterion

w_j = weight of importance of j^{th} criterion
N = Number of decision criteria
M = Number of alternatives

Weighted product method is very similar to the weighted sum method. In weighted sum method Addison is used where in weighted product method multiplication is used. The relative importance of a variable is calculated with comparing two variables using equation 2.4 and then compared with each other. If $R(A_K/A_L)$ is greater than one, the alternative A_K is better than the alternative A_L if the objective is for maximisation (Chang & Yeh, 2001).

$$R\left(\frac{A_K}{A_L}\right) = \sum_{j=1}^{N} \left(\frac{a_{kj}}{a_{Lj}}\right)^{w_j} \tag{2.4}$$

Where;
A_K and A_L = Alternatives compared
a_{ij} = Actual value of the i^{th} alternative in terms of j^{th} criterion
w_j = weight of importance of j^{th} criterion
N = Number of decision criteria

2.7.2 Analytical hierarchy process (AHP)

Analytic Hierarchy process (AHP) is a method that derive ratio scales from paired comparisons and also allows some small inconsistency in judgment. For the inputs it is possible to use actual measurements or subjective opinions and as output scales and consistency index is received. The AHP process is listed as follows (Golden, Wasil, & Harker, 1989).

Step 1: Define objectives

Step 2: Structure elements in criteria, sub-criteria, alternatives etc

Step 3: Make a pair wise comparison of elements in each group

Step 4: Calculate weighting and consistency ratio

Step 5: Evaluate alternatives according to weighting

Step 6: Get ranking

Table 2.5: Value of importance in AHP fundamental scale (Pohekar & Ramachandran, 2004)

Scale value	Level of importance
1	Equal importance
3	Moderately more important
5	Strongly more important
7	Very strongly important
9	Extremely more important

A scale of 1-9 is used to assess the preference or intensity between two alternatives. The value of importance in each number is presented in table 2.5. The values missing in the table (2,4,6,8) have been introduced to compromise the importance values.

The final weight coefficients presents the value of relative importance of the each alternative. The matrix in equation 2.5 reflect the method used to conduct the pair wise comparison of elements i with j in to the a_{ji} position.

$$M = \begin{bmatrix} a_{11} & a_{12} & .. & a_{1n} \\ a_{21} & a_{22} & .. & a_{2n} \\ a_{n1} & a_{n2} & .. & a_{nn} \end{bmatrix} \tag{2.5}$$

AHP calculates the inconsistency index which reflects the inconsistency of the decision maker and the randomly generated data. This is an advantage for the decision maker to make sure the judgment is consistent and it can lead to the final decision making as well. The inconsistency index should be less than 0.1 and if it if higher, re-evaluation of the comparison should be made (Pohekar & Ramachandran, 2004).

2.7.3 Multiattribute utility theory (MAUT)

Multi attribute utility theory (MAUT) considered the preferences of the decision makers in the form of utility function defined over a set of attributes (Pohekar & Ramachandran, 2004). The utility value can then be defined by determining single attribute utility functions and then verified by utility and preferential independent conditions and finally the multi attribute utility functions are derived.

This utility function can be either sperate by addition or multiplication with respect to single attribute utility. The multiplicative superable form for the utility value is presented in equation 2.6.

$$1 + ku(x_1, x_2, ...x_n) = \prod_{j=1}^{n}(1 + kk_j u_j(x_j)) \tag{2.6}$$

Where;
j = index of attribute
k = overall scaling constant (≥ 1)
k_j = scaling constant for attribute j
$u(x)$ = overall utility function operator
$u_j(x)$ = utility function operator for each attribute j

2.7.4 The elimination and choice translating reality (ELECTRE)

The elimination and choice translating reality (ELECTRE)is a method that can handle both quantitative and qualitative discrete criteria and provides an order of the alternatives (Botti & Peypoch, 2013). This method eliminates the less favourable alternatives which will create a clear view when associating with large number of alternatives for the decision making Figueira, Mousseau, and Roy (2005). In this technique concordance, threshold values and discordance indices are used and based on these indices, graphs are developed for strong and weak relationships. The alternatives are ranked using these graphs through an iterative procedure. This further calculates the global concordance (C_{ik}) which reflect the concordance among the criteria. It is further hypothesised that A_i outranked A_k and the global concordance is defined as given in equation 2.7.

$$C_{ik} = \frac{\sum_{j=1}^{m} W_j c_j(A_i A_k)}{\sum_{j=1}^{m} W_j} \tag{2.7}$$

Where;
W_j = Weight associated with j^{th} criteria

2.7.5 The technique for order preference by similarity to ideal solutions (TOPSIS)

The technique for order preference by similarity to ideal solutions (TOPSIS) is considered as an alternative to the ELECTRE which was discussed above. In this method, the alternatives are selected such that they have a shortest distance from the negative ideal solution J.-J. Wang, Jing, Zhang, and Zhao (2009). Firstly, a decision matrix for M number of alternatives and N number of criteria is formed and then, normalised and weighted decision matrices are prepared. Then, the ideal and negative ideal solutions are generated and after the seperation measure, the relative closeness to ideal solution is calculated. In this method, the alternative with longest distance to negative ideal solution and the shortest distance to ideal solution is considered as the best solution Pohekar and Ramachandran (2004).

2.7.6 Preference ranking organisation method for enrichment evaluation (PROMETHEE)

Preference ranking organization method for enrichment evaluation (PROMETHEE) is an outranking method which rank the alternatives with lesser complexity. The pair wise comparison in PROMETHEE rank the alternatives with reselect to several criteria. Brans, Vincke, and Mareschal (1986) has defined six generalised criteria for the reference as below.

- Usual criterion
- Quasi criterion
- Criterion with linear preference
- Level criterion
- Gaussian criterion
- Criterion with linear preference and indifference area

The multi-criteria preference index and the net ranking in this method is presented in equation 2.8 and generally the minimum $\phi^+(a)$ is considered as the best solution Pohekar and Ramachandran (2004).

$$\begin{aligned} \pi(a,b) &= \frac{\sum_{j=1}^{J} w_j P_j(a,b)}{\sum_{j=1}^{J} w_j} \\ \phi^+(a) &= \sum_{A} \pi(a,b) \\ \phi^-(a) &= \sum_{A} \pi(b,a) \\ \phi(a) &= \phi^+(a) - \phi^-(a) \end{aligned} \tag{2.8}$$

Where;
$P_j(a, b)$ = Preference function (Function of the difference d_j between two alternative for any j criterion
$d_j = f(a, j) - f(b, j)$
(a, j) = Value for alternative a for criterion j
(b, j) = Value for alternative b for criterion j
$\pi(a, b)$ = Weighted average of the preference functions
w_j = Weight assigned to the criterion j
$\phi^+(a)$ = Outranking index of a (in the alternative set A)
$\phi^-(a)$ = Outranked index of a (in the alternative set A)
$\phi(a)$ = net ranking of a (in the alternative set A)

2.8 Summary

The existing rating systems fall into either calculated rating or measured rating. Using only one rating method may not provide the true picture on the energy consumption scenario of the building and therefore, several attempts are there to make a hybrid method. The only available hybrid system is MOHOURD system in China although the integration is not yet successful. Therefore, a new system should be made with both assets and measured rating, which can be altered easily based on policy changes, country and climate. When evaluating the building energy performance, thermal comfort receives a special emphasis. For tropical climates, specially for naturally ventilated buildings, ASHRAE 55 adaptive comfort standards provide better thermal comfort perceptions and can be used for thermal comfort calculations for naturally ventilated buildings. This standard uses a prevailing mean outdoor temperature, which can be specific to the climate and then the upper and lower limits of the operative temperature can be vary based on the prevailing mean outdoor temperature and the air flow rates. In addition to thermal comfort, the lighting energy also depends on the building characteristics. The window to wall ratio, orientation and other properties such as building shape can contribute to the lighting energy. The previous works related to the thermal comfort optimisation are much aimed at heating and cooling demand, rather focusing on naturally ventilated residential buildings. Also, the effect of zones on thermal comfort and lighting are highly neglected in the past studies. Therefore, the methodology should focus on the effect of zones and zone locations of the naturally ventilated buildings.

In addition to the building properties, consumer behaviour affects significantly to the energy performance of the building. The floor area of the building has a significant effect on the energy consumption specially if heating and cooling is involved. The door and window opening behaviours and equipment usage, maintainable and purchase decisions are highly affected by various occupant characteristics and need to be considered in developing the energy rating. finally, the sustainability assessment of energy sources are mainly in three main categories as social, economic and environmental and when using an index value for sustainable assessment of energy sources, all these aspects should be considered. The next chapter would provide more detailed information regarding the research approach and the methodology of developing the rating system.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 General

This research is aimed at identifying the existing rating systems, investigate the existing systems, to identify the parameters required for determining the energy performance of residential buildings, to develop and equation for calculating the energy score and to develop a scale for comparing the energy performance of residential buildings in hot and humid climate in Sri Lanka. The research methodology is based on the sustainable energy concept and this chapter discusses the development of the sub ratings, optimum house development and questionnaire survey design.

3.2 Research approach

The aim of the energy rating system is achieving sustainable energy consumption goals. The two pillars of sustainable energy could be identified as energy efficiency and renewable energy. The energy efficiency could be achieved through optimizing the building characteristics and sustainable occupant behavior. Therefore, the parameters that should be considered for the energy rating can be identified as the energy sources, building characteristics and the occupant behavior. The environmental conditions including the macro and micro climatic conditions, will affect the characteristics of the building and therefore the environment is also included under the building characteristics. Further, the equipment type and usage also depend heavily on the occupant characteristics, hence it is also categories under the occupant characteristics.

While the sustainability of the energy consumption depends on the above three conditions, the weightage that should be put on each condition will be different based on the country, climate and the country energy policies.

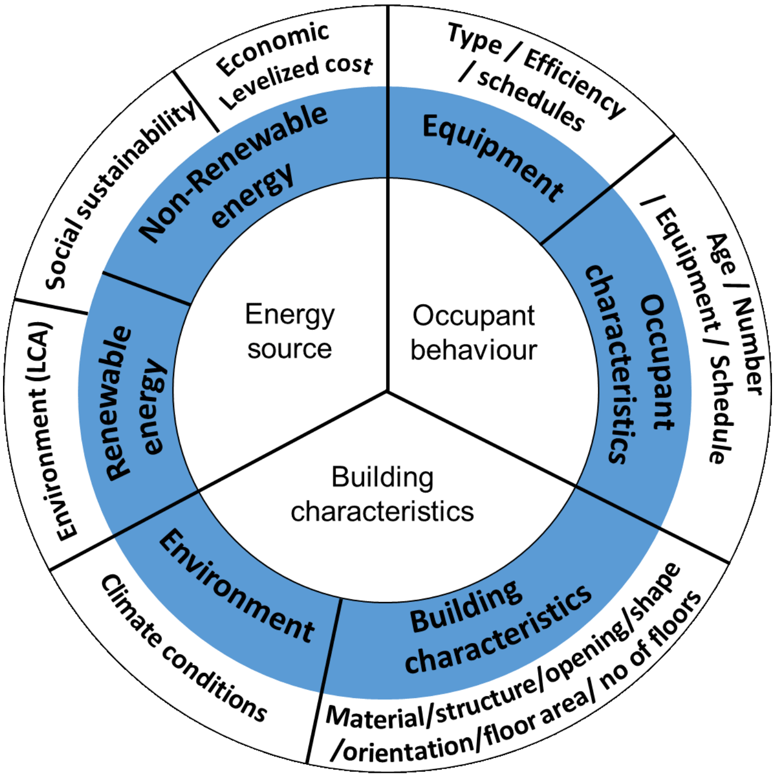


Figure 3.1: Parameter categorisation

In the bill based methods, all the above criteria are considered if net zero energy also involved. However, the contribution of each conditions cannot be measured or evaluated using those methods. This kind of separation of the variables would allow the rating system to change easily based on the policy changes and the changes in the urban environment. The final output of the energy rating system provides a score (in 100 scale) based on a function of following variables.

- BC_{rate} (Building consumption rate) The rate based on the energy consumption due to building characteristics
- OB_{rate} (Occupant Behaviour rate) The rate based on the energy consumption due to occupant behaviour
- ES_{rate} (Energy source rate) The rate based on the sustainability assessment of the energy sources

$$ER = f(BC_{\text{rate}}, OB_{\text{rate}}, ES_{\text{rate}}) \tag{3.1}$$

The overall methodology of the research is illustrated in figure 3.2

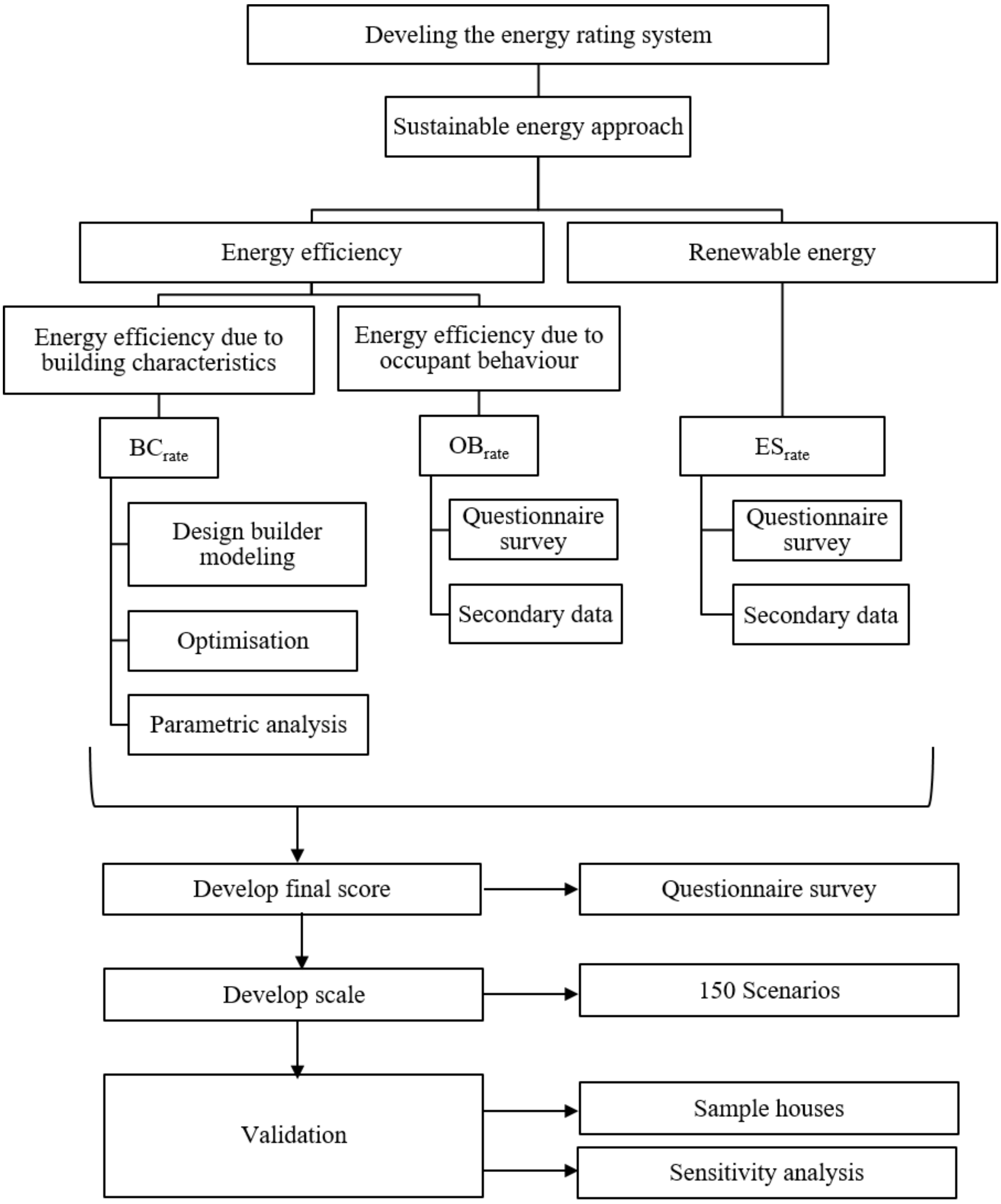


Figure 3.2: Overall methodology of the research

3.3 $BC_{\mathbf{rate}}$ (Building consumption rate) calculation

For energy rating systems, the performance based rating systems are preferred rather than the feature specific systems. Therefore in the BC_{rate} calculation, dynamic simulation with forward modeling is used. Using simulation, the energy consumption for achieving the minimum lighting and thermal comfort requirement (BC_A) of the house are identified. For the scaling purpose the optimal building consumption (BC_{optimal}) are also identified by modeling.

$$BC_{\text{rate}} = \frac{BC_{\text{optimal}}}{BC_A} \times 100 \tag{3.2}$$

3.3.1 BC_A calculation

The calculation of the energy requirement for lighting and thermal comfort for actual building depends on whether the building is naturally ventilated or air conditioned. Therefore, the methods to calculate BC_A for those two types of buildings are discussed separately.

3.3.1.1 BC_A calculation for air conditioned buildings

BC_A is the energy required to achieve the minimum lighting requirement and the thermal comfort requirement at typical or optimal cooling set point. For air conditioned building, controlling both lighting and thermal comfort is easier and the energy required to achieve that level can be easily modeled. Therefore, BC_A for air conditioned building can be obtained from the direct modeled data.

3.3.1.2 BC_A calculation for naturally ventilated buildings

The building contribution of the actual building depends on the energy required for the lighting (BC_{LA}) and the energy required for achieving the thermal comfort (BC_{TCA}).

$$BC_A = BC_{\text{LA}} + BC_{\text{TCA}} \tag{3.3}$$

The energy required for achieving the lighting can be easily obtained by the lighting simulation using Design Builder model. However, if the building uses only natural ventilation and fans then, it will be difficult to identify the real building contribution to achieve the thermal comfort. For example, a house with poor design and materials will have similar building contribution (thermal comfort) that a house with better design and material. In that case there will not be any difference between the optimal house and the actual house. The energy used for the fans will only depend on the fan power, number of fans and the schedule. In this case it will be difficult to differentiate an optimal house with a poorly designed house. In order to solve this issue, a proper method should be used to control the fan usage based on the thermal comfort inside the house.

3.3.1.3 $BC_{\mathbf{LA}}$ calculation

BC_{LA} is the energy required to achieve the minimal lighting level of the house. When calculating this, the data related to the lighting and natural ventilation should be included to have a proper simulation. The final energy consumption received from this input is considered as BC_{LA}.

3.3.1.4 $BC_{\mathbf{TCA}}$ calculation

BC_{TCA} is the thermal comfort building contribution which cannot be obtained from the modeling. This element totally depends on the energy consumption by individual fan, number of rooms and the occupancy schedules. For the energy consumption per fan the values for energy efficient ceiling fans can be used. For the number of fans, it is assumed that each room bedroom, kitchen and living area have fans. For living area, more than one fan have to be used to cover the total area and it is calculated by dividing the total area by the area covered by one ceiling fan. Each of the other zones (bedrooms and kitchen) are provided with one ceiling fan unless the floor area cannot be covered by a single ceiling fan.

$$\text{Upper 80\% acceptability limit } ({}^{0}C) = 0.31\overline{t_{pma(out)}} + 21.3 \tag{3.4}$$

The schedule for operating the ceiling fan is decided based on the discomfort hours in ASHRAE 55 standard 80% acceptability with various air velocities. The upper limits of operative temperature for 80% acceptability can be calculated using equation 3.4 and this temperature increases with the air speed. For those air speeds, the required fan power is determined and those power requirement is used to determine the fan power used when the comfort conditions are not met. The detailed calculations and descriptions are available in section 4.4. Finally, the BC_{TCA} can be calculated using equation 3.5.

$$BC_{TCA} = \sum_{i=1}^{n} F_i(P_L h_{Li} + P_M h_{Mi} + P_H h_{Hi}) \tag{3.5}$$

Where;
BC_{TCA} = building contribution for thermal comfort in the actual building
i = zone
F = number of fans
P = power of the fan
h = number of hours the fan is operation
L = low speed
M = medium speed
H = high speed
n = number of zones

3.3.2 BC_O calculation

When considering the optimal building, if the indoor temperature can be maintained in the comfort zone with the help of mechanical ventilation, then the buildings can withstand without air conditioning. Further, with the thermal adaptation, the people who live in climate with higher average temperature would have higher tolerance regarding the thermal comfort requirement Halwatura (2014). However it is difficult to compare the naturally ventilated optimal building with the air conditioned actual building when checking the building characteristics. Therefore, if the actual house is air conditioned, the optimal building also will be modeled for air conditioning.

3.3.2.1 Naturally ventilated buildings

Further, this optimal building design would be limited to two story houses since the majority of the urban houses in the hot and humid climate comprises of two story houses. Therefore the building energy consumption (BC_O) only depends on the number of rooms and the outside temperature. As this optimal building is naturally ventilated, calculating building contribution is almost similar to any naturally ventilated building. The building contribution of the actual building depends on the energy required for the lighting (BC_{LO}) and the energy required for achieving the thermal comfort (BC_{TCO}).

$$BC_{\mathrm{optimal}} = BC_{\mathrm{LO}} + BC_{\mathrm{TCO}} \tag{3.6}$$

BC_{LO} will be the energy required to achieve the minimal lighting level of the house. When calculating this the data related to the lighting and natural ventilation should be included to have a proper simulation. The final energy consumption received from this input will be considered as BC_{LO}. BC_{TCO} value is similar to BC_{TCA} as already presented in equation 3.5. However, as discussed in the section 4.4, for some cases (eg: two story three bedroom houses), the number of fans can be minimum.

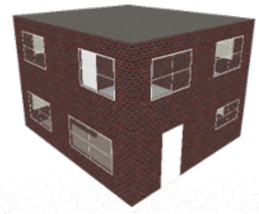
3.4 Analysing the effect of building shape and zones

To analyse the effect of building shape and zones a case study was conducted using 300 different building models prepared using Design Builder software.

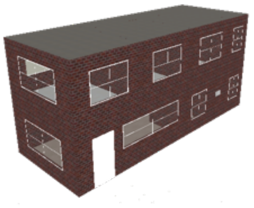
3.4.1 Case study models

The case study model houses comprised of three bedrooms, one living room, one bathroom and one kitchen. A hypothetical location at Katunayake, Sri Lanka was used for the simulation and the climate in Katunayake is tropical hot humic which falls in to ASHRAE 1A climate zone. In Sir Lanka, the average family size is four (Department of Census and Statistics, 2012) and therefore, the number of occupants were set as four in the model. The average number of living spaces per permanent house is 4.4 (Department of Census and Statistics, 2012) and therefore, the model house was designed including five living spaces (three bedrooms, one kitchen and one living area). The highest domestic energy consumption is evident in urban areas and in Colombo district 22.3% houses are two story houses (Department of Census and Statistics, 2012). Therefore, two story houses were selected for this model, although majority of Sri Lankan houses are one story. The gross floor area was maintained at $68m^2$ for each house model and height of each floor is 3.01m. Figure 3.3 illustrates the external dimensions of the model houses. For each zone, the minimum dimensions were defined based on Neufert guide (Neufert & Neufert, n.d.) as shown in table 3.2.

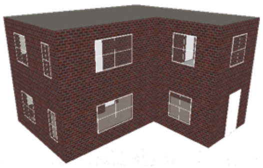
In order to maintain the same gross floor area, to easily change the shape and arranging zones, all bedrooms were placed in first floor and other zones were placed in the ground floor. This bedroom arrangement facilitated three different building shapes; square shape, rectangular shape and L shape. In each shape, the location of staircase was changed resulting seven main cases figure 3.4). For each case, the location of bathroom and kitchen was changed relative to the location of staircase and the zone sizes (bathroom, kitchen and living) were changed (figure 6,7 and 8). For all these sub cases, the zone sizes (kitchen and bathroom) were started from the minimum sizes (table 3.2) and were increased creating more cases.



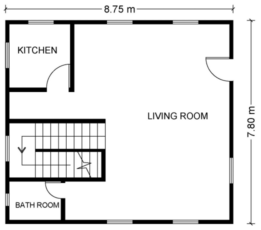
(a) Square shape model



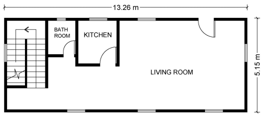
(b) Rectangular shape model



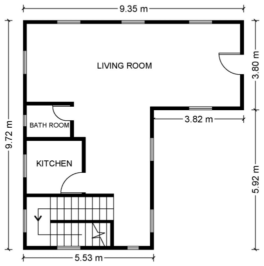
(c) L Shape model



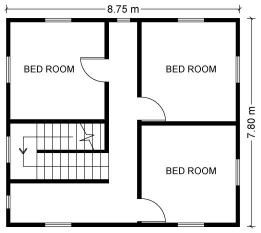
(d) Square shape model ground floor plan



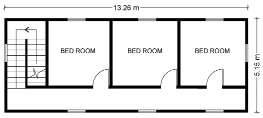
(e) Rectangular shape model ground floor plan



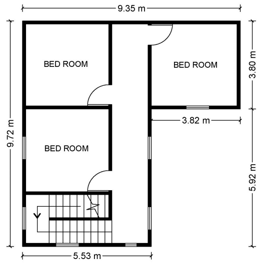
(f) L Shape model ground floor plan



(g) Square shape model first floor plan



(h) Rectangular shape model first floor plan



(i) L Shape model first floor plan

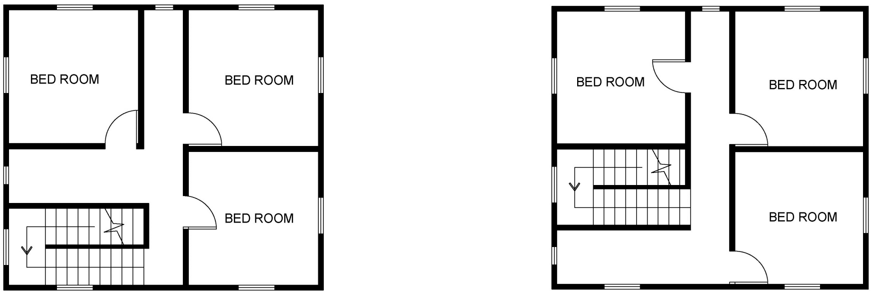
Figure 3.3: Samples of case study house models

Table 3.1: Descriptive Statistics of the pilot survey (N=120)

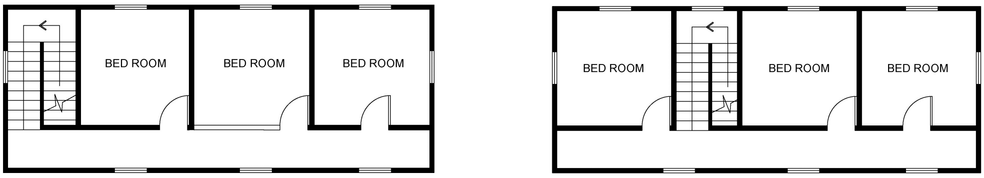
	Minimum	Maximum	Mean	Std. Deviation
Number of occupants	2	8	4.47	0.98
Number of floors	1	4	1.52	0.67
Number of bedrooms	1	6	3.59	0.95
Leave home	5.30 AM	10.00 AM	7.14	0.75
Return home	2.00 PM	12.30 AM	5.03	1.14
Light switch on	3.00 AM	8.00 AM	5.01	1.06
Light switch off	8.00 PM	12.30 AM	10.12	1.24

Table 3.2: Minimum internal dimensions of the zones

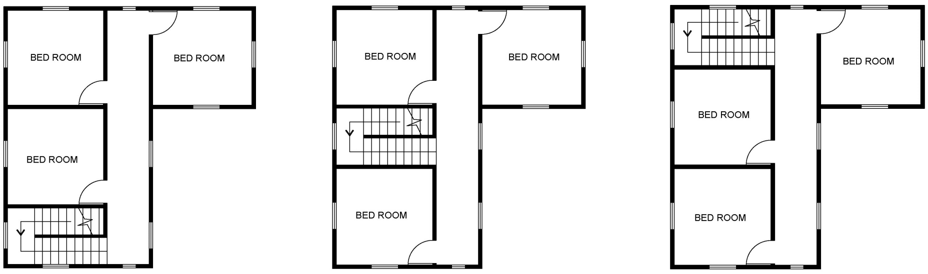
Zone	Length	Width
Kitchen	2.4 m	2.3 m
Bedroom	3.6 m	3.5 m
Living (Including dining area for 6 people)	4.8 m	3.3 m
Bathroom	1.6 m	1.4 m



(a) S case 1 - staircase at the corner (b) S case 2 - staircase at the middle



(c) R case 1 - staircase at the corner (d) R case 2 - staircase at middle



(e) L case 1 - staircase at short corner (f) L case 2 - staircase at middle (g) L case 3 - staircase at long corner

Figure 3.4: Staircase positions of the house models and the seven cases

3.4.2 Simulation settings

For the external and internal wall of the models burnt brick was selected as it is the mostly used (53.2% of the houses (Department of Census and Statistics, 2012)) walling material in Sri Lanka. Table 3.3lists the U-values and thicknesses of external and internal walls, floor, roof and glazing. Heating and cooling were disabled in the HVAC tab and natural ventilation was set as always on. In order to facilitate higher natural ventilation, 5 ac/h was used as outside air exchange rate. The activity template had 0.5 Clo value and metabolic rate of 123W per person and the house model was designed for four people. A pilot survey was conducted to identify the occupancy, lighting and door/window opening schedules and as per the results, the occupancy schedule was set as 5 pm to 7 am next day.

In residential buildings, it is difficult to generalize the lighting requirements as it mainly depends on the specific requirements and behavior of the occupants. In a single family house, the average illuminance levels for spaces such as bedrooms, kitchen, living and bathroom varies from 100 to 200 lux (CIBSE, 2013). All the other zones except kitchen requires only 100 to 150 lux illuminance level. In this case study, as a reasonable estimate, 150 lux was set as the target illuminance for all the spaces as in the houses higher lighting levels are normally not required. To get at least 0.5 points for the reduction of lighting power density (LPD) in LEED certification, the single family houses should not exceed LPD of 7.7 W/m^2 (U.S. Green Building Council, 2018). Considering the tendency of Sri Lankan households to move to high efficacy lighting, LPD of 7.7 W/m^2 was used as the reference and the normalised power density was set as 5 $W/m^2 - 100$lux.

Table 3.3: Material details of the construction components

Component	Thickness	U value(W/m2-K)
External wall (Burnt brick - Internal surface finished with cement/sand /limestone motar)	0.137m	2.997
Internal walls (Burnt brick - surfaces finished with cement/sand /limestone motar)	0.147m	2.874
Floor	0.3327m	0.25
Roof	0.3675m	0.25
Glazing (Double pane clear glass)	3mm	0.9

Table 3.4: Objectives and design variables of the optimisation

Objectives	Design variables
Minimise lighting electricity	Window to wall ratio (20, 40, 60, 80)
Minimise discomfort hours (ASHRAE 55 adaptive 80% acceptability)	Orientation (0 to 345^0)

Cement/sand/limestone mortar ws used to finish the interior walls and painted with white colour. To control the light as per day lighting illuminate, the lighting control option was set on. Based on the pilot survey results, the lighting schedule was selected as 5 am to 10 pm. For the simulations and optimisation, Design Builder version 5 software was used. In total, 300 different housing models were developed varying the building shape, zone location, zone size and staircase position. The models were optimised using two objectives and two design variables (WWR and orientation) as shown in table 3.4. All the electricity loads except artificial lighting electricity were removed in the settings and the electricity contained only the lighting electricity. Therefore, minimising the electricity could be considered as the first objective function which will ultimately minimise the lighting electricity. compared to the occupants in mechanically cooled (air-conditioned) houses, the occupants in naturally ventilated houses can accept wider temperature variations and higher indoor temperatures (ASHRAE, 2010). As discussed in the literature review, adaptive comfort models like ASHRAE 55 facilitate such wide range of temperatures and therefore, minimum discomfort hours as per ASHRAE 55 80% acceptability was used as the second objective function.

3.5 Parametric analysis of the optimal form

After completing the simulations as described in section 3.4, a parametric analysis had to be conducted to identify the proper relationship across the variables. Using 4569 different models simulations were run to calculate the discomfort hours and lighting electricity. As per the results of the simulations (4.2, the following variables were identified as important.

- Zone sizes
- Location of the staircase
- Location of the zones

- Shape of the house
- Building orientation
- Window to wall ratio
- Total floor area

However, for the parametric study, the variables have to be measurable and therefore, the above variables were subdivided to 31 independent variables as follows which covers all the seven factors.

1. Total area of the building (TBA)
2. Roof area (RA)
3. Ground floor bathroom area (GFBA)
4. Ground floor kitchen area (GFKA)
5. Ground floor living area (GFLA)
6. Ground floor bedroom 1 area (GFBR1A)
7. Ground floor bedroom 2 area (GFBR2A)
8. First floor bedroom 1 area (UFBR1A)
9. First floor bedroom 2 area (UFBR2A)
10. First floor bedroom 3 area (UFBR3A)
11. First floor corridor area (UFCRDA)
12. North faced wall area (NWA)
13. South faced wall area (SWA)
14. West faced wall area (WWA)
15. East faced wall area (EWA)
16. North faced window area (NWIA)
17. South faced window area (SWIA)
18. West faced window area (WWIA)

19. East faced window area (EWIA)
20. Kitchen - North faced wall area (KEWNA)
21. Kitchen - South faced wall area (KEWSA)
22. Kitchen - West faced wall area (KEWWA)
23. Kitchen - East faced wall area (KEWEA)
24. Bathroom - North faced wall area (BEWNA)
25. Bathroom - South faced wall area (BEWSA)
26. Bathroom - West faced wall area (BEWWA)
27. Bathroom - East faced wall area (BEWEA)
28. Staircase - North faced wall area (SCEWNA)
29. Staircase - South faced wall area (SCEWSA)
30. Staircase - West faced wall area (SCEWWA)
31. Staircase - East faced wall area (SCEWEA)

In the optimisation simulations, two main outputs were generated as thermal discomfort hours (D) and lighting electricity (E_L). Typicallythere are two main approaches to solve the multi objective optimisation problems: Pareto based approach and weighted sum approach. The Pareto frontier approach defines how each objective affect each other and this is not performed in weighted sum approach. In the second approach a unique objective is defined as the weighted sum of the sub objectives. In this study several solutions were selected for each model (nearly 20 solutions for each model) and this was be used to get the weighted sum of the objectives using the objective function given in equation 3.7.

$$E_{\text{tot}} = E_{\text{TC}} + E_L \tag{3.7}$$

Where;
E_{tot} = Total Electricity consumption
E_{TC} = Electricity consumed for thermal comfort

E_L = Electricity consumed for lighting

The lighting electricity (E_L) is a direct output in the Pareto solution and can be directly applied to the equation 3.7. However the electricity consumed for thermal comfort (E_{TC}) is not a direct output and it has to be derived from the thermal discomfort hours (D). To minimise the thermal discomfort it is assumed that ceiling fans (size of the blade = 120cm) with maximum power is used (75W) for each important space of the house (bedrooms living dining kitchen). The number of ceiling fans required is calculated based on the area covered by one ceiling fan (equation 3.8).

$$S = \Pi R^2 \tag{3.8}$$

Where;
R = radius of effective floor space of wind spread (m)= [coefficient (0.65 for 120cm blade) x H (2.5 for 120cm blade)]
S = effective floor area (m^2)

According to the calculation the rough area covered by one ceiling fan is $8.3m^2$. Based on that the number of ceiling fans required for the zone can be determined and the E_{TC} can be calculated using 3.9

$$E_{\mathrm{TC}} = \frac{P \times t \times N}{1000} \tag{3.9}$$

Where;
E_{TC} = Electricity consumed for thermal comfort
P = Ceiling fan power consumption (75W)
t = Discomfort hours
N = Number of fans

Using the new objective function the function given in equation 3.10 was used for the parametric analysis of building form.

$$E_{\mathrm{tot}} = f(x_1, x_2, ..., x_{31}) \tag{3.10}$$

Where; x denotes the each parameter considered in the analysis.
For the statistical analysis SPSS version 24 software was used.

3.6 Optimum building design

Based on the results of the parametric analysis (section 4.3), the optimal form of the house was developed while considering the local building regulations. The considered minimum internal dimensions as per the building regulations are presented in table 3.5(Urban Development Authority, 2005).

Table 3.5: Internal dimensions Building regulations of Urban development authority, Sri Lanka (Urban Development Authority, 2005)

Zone	Minimum extent (m^2)	Minimum length (m)	Minimum width (m)
First room	8.5	-	2.4
Additional room	7.5	-	2.4
Kitchen	5.5	-	1.8
Combined bath and toilet	-	.9	1.7

In addition to the internal dimensions, the following regulations were also considered during the optimal building design.

- The minimum height for the corridors, bathrooms and toilets is 2.1 meters
- The minimum height for other rooms except corridors, bathrooms and toilets is 2.7m
- In case of sloping roof, the height at the mid point should be 2.4m and the lowest height at any point should be 2.1m

For natural light and ventilation requirements the area of opening and percentage of area openable was decided based on table 3.6.

Table 3.6: Area of openings as per Building regulations of Urban development authority, Sri Lanka (Urban Development Authority, 2005)

Zone	Area of opening	% of area openable
Bathroom and toilet	1/10	100
Other rooms	1/7	50

Furthermore, the maximum distance allowed from the opening was considered as 10m and the maximum perpendicular distance allowed from the edge of the opening was taken as 3m according to the same regulations (Urban Development Authority, 2005). The developed building form was then modified to achieve the best energy efficiency by changing the parameters such as building materials, shading, roof type etc.

3.7 $OB_{\mathbf{rate}}$ (Occupant behaviour rate) calculation

The occupant behavior rate is the portion of the energy which depends on the behavior of the occupant. The energy bill represents the entire aspects about the behavior of the occupants in the household such as the lighting and thermal comfort requirement, selection of the building materials and types, equipment and usages, number and the nature of the occupants etc. Therefore, in this OB_{rate} calculation, the total monthly electricity consumption was considered for the evaluation purpose. The reference values were obtained through a questionnaire survey.

3.7.1 Development of the questionnaire

The questionnaire was prepared with the aim of getting the following information.

- Average monthly energy consumption (Units)
- Floor area of the house
- Number of stories
- Number of bedrooms
- Occupant details

  Number of occupants in each age group
- Equipment details

  Equipment used and number (TV, Refrigerator, Washing machine, Desktop computer, laptop computer, Hot water heating system, and Other equipment)

- Lighting, ventilation and cooling details

  Ventilation and cooling systems (type and number)

  Schedules (occupancy schedules, door and window opening schedules, and lighting schedules)

Five hundred questionnaires were distributed, and received 390 filled questionnaires, resulting 80% response rate.

3.7.2 OB_{rate} calculation

The OB_{rate} can be calculated using equation 3.11. The method of calculating the average energy consumption is discussed in section 4.5.

$$OB_{rate} = \frac{\text{Actual energy consumption}}{\text{Average energy consumption}} \times 100 \tag{3.11}$$

3.8 ES_{rate} (Energy Source rate) calculation

Most of the energy rating systems in the world which consider energy sources offset the total energy consumption with renewable energy. In order to check whether there are other social and technical effects associated with renewable energy, a questionnaire survey was conducted to take the decision on whether to offset the total energy consumption with renewable energy or to use or develop a sustainability index.

3.8.1 Sustainability assessment of rooftop solar PV in residential buildings

The principal objective of this study was to assess the sustainability of the rooftop solar PV net metering policies in Sri Lanka. The analysis is based on the net metering policies and electricity tariffs of domestic sector offered by Public Utilities Commission, Sri Lanka. The primary approach associated with this study is a quantitative and qualitative analysis of two data sets. The first dataset includes information about the characteristics of a sample of residential rooftop solar PV installed customers and the installation and consumption details in Sri Lanka. A questionnaire survey was conducted from April to August 2017 through email. The questionnaire fields include the location of the solar installed property number of people in household year of solar PV installation energy storage model average energy consumption (units) before installation average energy consumption (units) after installation (including self-generation and from grid) excess units supplied to grid equipment used before installation and equipment purchased after solar PV installation reasons for increase in energy consumption changes happened in the household after installation and the motivation to have solar PV system. The questionnaire was sent to 100 rooftop solar PV customers and 52 valid responses were received. The second dataset is a supplementary dataset obtained from the energy balance data of Sri Lanka Sustainable Energy Authority (SLSEA, 2017). The data fields include; the electricity consumption in each sector Gross Domestic Production (GDP) at 1982 factor cost electricity generation by various sources (hydro thermal wind new renewable energy and net metered projects) and average electricity prices from 1976 to 2015

3.8.2 Sustainability index for energy sources

According to the literature, the sustainability criteria for energy sources are mainly falling to social, economic and environment categories. As discussed in the literature review, most of the sustainability assessment of energy sources present a qualitative measure rather than a quantitative measure. However, Cartelle Barros et al. (2015) has conducted a sustainable energy assessment without limiting to qualitative analysis and provided a methodology to calculate the sustainability index of the energy sources. Cartelle Barros et al. (2015) calculated sustainability indexes for ten energy sources and used MIVES method to develop the model.

3.8.2.1 MIVES method

MIVES method (Modelo Integrado de Valor para una Evaluacion Sostenible) is also known as the "Integrated Value Model for Sustainability Assessment". This is an existing method which is used for assessing the sustainabile design of the concrete structures (Del Cano, Gomez, & De La Cruz, 2012) and select urban pervious pavements (Jato-Espino, Rodriguez-Hernandez, & Ballester-Munoz, 2014). The process in MIVES method includes seven different phases as indicated in figure 3.5

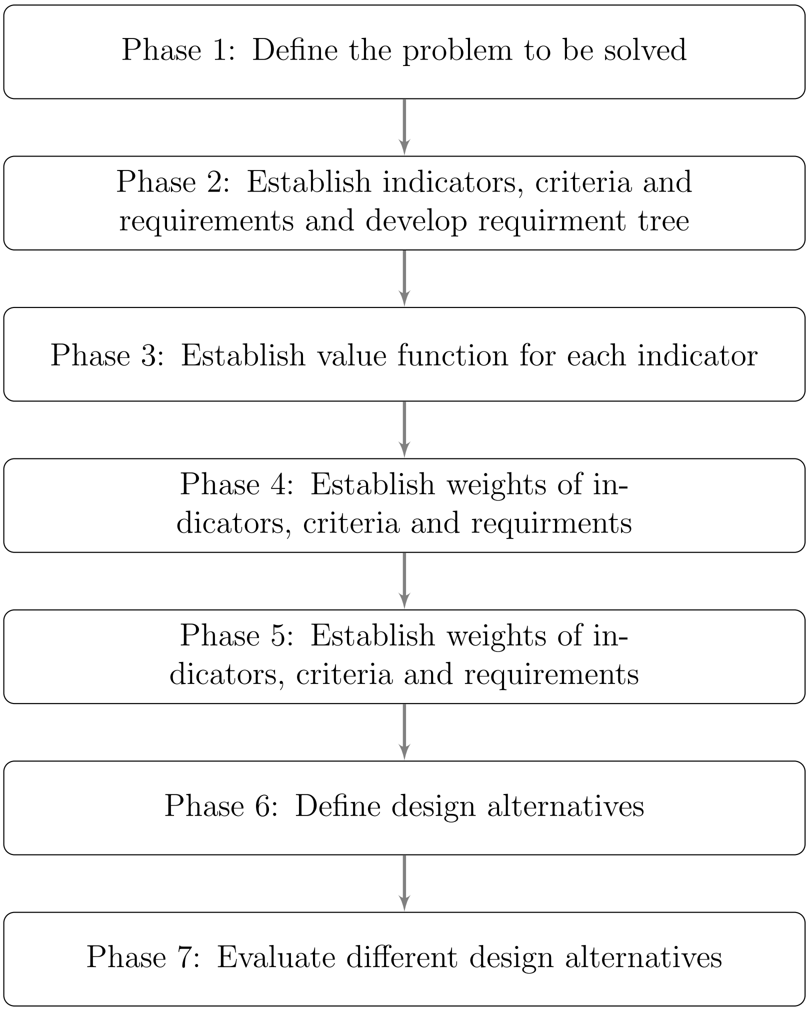


Figure 3.5: The different phases in the MIVES method (Cartelle Barros et al., 2015)

For x number of alternatives, for N number of value functions and if P_x is the set of indicators, γ_k is the relative importance of each indicator and V_k is the value function of each indicator, then the dimensionless global value ($V(P_x)$) can be illustrated as in equation 3.12

$$V(P_x) = \sum_{k=1}^{N} \gamma_k . V_k(P_{k,x}) \tag{3.12}$$

In order to make the equation to a tree structure (with requirements (r), criteria (c) and indicators (i), the following process has been carried out.

- *Add the indicators belong to same criterions* – If N_i is the number of indicators belong to criterion c and γ_i is the factors representing weighting of different indicators (i), the value function for a particular criteria and for a particular alternative is expressed in equation 3.13.

$$V_c(P_{c,x}) = \sum_{i=1}^{N_i} \gamma_i.V_i(P_{i,x}) \tag{3.13}$$

- *Add functions of criteria belong to same requirements* – If r is requirement, N_c is number of criteria belonging to requirement r and β_c is the factors representing weighting of different criteria, the value function for particular requirement and for particular alternative is expressed in equation 3.14.

$$V_r(P_{r,x}) = \sum_{c=1}^{N_c} \beta_c.V_c(P_{c,x}) \tag{3.14}$$

- *Add functions for requirements to get total value function (global sustainability index) for alternative x* – If N_r is the number of requirements in the tree and α_r is the weight for different requirements then the total value function for a particular alternative is expressed in equation 3.15.

$$V(P_x) = \sum_{r=1}^{N_r} \alpha_r.V_r(P_{r,x}) \tag{3.15}$$

- *Combine all the equations* – If α_i is weight for requirement, β_i is weight for criteria and γ_i is weight of indicators, and $V_r(P_{r,x}$ is the value function to measure the degree of sustainabililty of alternative x, then the global value function for particular alternative is expressed in equation 3.16.

$$V(P_x) = \sum_{r=1}^{N} \alpha_i \beta_i \gamma_i.V_i(P_{i,x}) \tag{3.16}$$

In order to homogenize the units of indicators by bringing all the values of the value function to 0 - 1 range, the equation 3.17 is used. Here, $P_{i,x}$ is the input value of the indicator i for alternative x, and n_i, m_j, and A_i are the shape factors to generate concrete, s-shaped, convex or straight line value functions.

$$V_i = \left[\frac{1 - exp(-m_i \left(\frac{|P_{i,x} - P_{i,min}|_i^A}{n_i} \right)}{1 - exp(-m_i \left(\frac{|P_{i,max} - P_{i,min}|_i^A}{n_i} \right)} \right] \tag{3.17}$$

Table 3.7: The requirement tree of the model with the weights (Cartelle Barros et al., 2015)

α_i	Requirements	β_i	Criteria	γ_i	Indicators
28%	Economic	15.85%	Raw material or fuel obtaining cost	100%	Cost of mining and extraction
		6.25%	Raw material or fuel preparation cost	100%	Cost of pre treatment and enrichment
		5.95%	Raw material or fuel transportation cost	100%	Transportation cost
		28.24%	Investment cost	100%	Investment cost
		42.04%	Operating cost	42.23%	Fuel cost and CO_2
				57.77%	Cost of operation and maintenance
		1.67%	Subsidies	100%	Subsidies
33%	Social	20.11%	Employment generation	100%	Generated employment opportunities
		8.02%	Population displacement due to project	100%	Population displacement
		8.02%	New areas development	100%	New areas development
		61.17%	Health and safety	100%	Risk of accident
		2.68%	Visual impact	100%	Visual impact
39%	Environmental	88.37%	Environmental impact	100%	Ecopoints of environmental impact
		4.86%	Discomfort of noise and odours	60%	Noise
				40%	Bad odours
		6.77%	Geographical impact	100%	Impact (Local, regional, global)

3.8.2.2 Assessment model by Cartelle Barros et al. (2015)

Using the MIVES model discussed in the above, Cartelle Barros et al. (2015) developed a sustainability index for energy sources as illustrated in 3.18. Here, α_i is weight for requirement, β_i is weight for criteria and γ_i is weight of indicators, and V_i is the value function. The requirement tree of the model with the weights is shown in table 3.7. Further, the sustainability index values for 10 different energy sources calculated by Cartelle Barros et al. (2015) is also available in table 3.8. These sustainability index values were used to calculate the index values for electricity generation scenarios in developing energy source rate (ES_rate)

$$SI = \sum_{i=1}^{16} \alpha_i \beta_i \gamma_i . V_i) \qquad (3.18)$$

Table 3.8: Sustainability index values (Cartelle Barros et al., 2015)

Energy source	Index breakdown for requirements			SI value
	Economic	Social	Environment	
Solar thermal	0.13	0.32	0.35	0.8
Wind	0.15	0.24	0.37	0.76
Photovoltaic	0.13	0.25	0.31	0.69
Hydro	0.16	0.06	0.39	0.61
Natural gas	0.16	0.14	0.27	0.57
Nuclear	0.18	0.08	0.14	0.4
Biomass	0.08	0.26	0.05	0.39
Oil	0.16	0.14	0.01	0.31
Coal	0.14	0.14	0.01	0.29
Lignite	0.14	0.14	0.01	0.29

3.9 Development of energy score and scale

When converting the developed BC_{rate}, OB_{rate} and ES_{rate}, to an energy score, the first step is to normalise the each rate to some common scale. For that purpose, 0 to 100 scale was used. For the conversion purposes equation 3.19 was used.

$$Normalisedrate = \frac{\text{Actural rate} - \text{Minimum rate}}{\text{Maximum rate} - \text{Minimum rate}} \tag{3.19}$$

3.9.1 Deciding the weights of the rates

The energy rating score is defined as a function of BC_{rate},OB_{rate},ES_{rate} in section 3.2. The function can be a linear function, a polynomial function or a more complex function based on the requirement. Here, in this research, the relationship between those variables were considered as a linear function as it will reduce the complexities of the final models and the alterations and the localisations of the model will be convenient. Therefore, the weighted sum of the three variables were considered as the final equation. As discussed in the literature review, various methods on determining the weightages are available and for this study the weighted sum approach was used as only the perception of different stakeholders are used at this point. However, in the actual implementation, with the policy initiatives, the methods such as analytical hierarchy process can be used considering several decision layers and by validating the responses.

In combining normalised values of BC_{rate}, OB_{rate} and ES_{rate}, weights should be assigned to bring to a single score. In order to decide the weights, a questionnaire survey was conducted involving civil engineers, electrical engineers, architects, quantity surveyors. The weights were based on the perception of the people who are actively involved in the industry. In total 193 responses were received. The questionnaire included three questions indicated below and the respondents were asked to provide scores from 1 (Not important) to 5 (Extremely important) based on their perception.

Question 1: According to your opinion, how do you allocate scores for the importance of the properties of buildings (Building envelope, window to wall ratio etc. which relates to thermal comfort and lighting requirements) in developing energy rating system for residential buildings.

Question 2: According to your opinion, how do you allocate scores for the importance of electricity consumption due to occupants' behaviour (occupancy schedules, lighting schedules, equipment usage etc.) in developing energy rating system for residential buildings.

Question 3: According to your opinion, how do you allocate scores for the importance of energy sources used to generate electricity (electricity from main grid, rooftop solar PV etc.) in developing energy rating system for residential buildings.

3.10 Summary

Considering the inadequacies of the existing systems, this research developed a new energy rating methodology which is based on sustainable energy concept. In this concept, both energy efficiency and the renewable energy sources are considered and in energy efficiency, the energy consumed due to building characteristics and due to occupancy behaviour are considered. Three ratings were prepared to cover each aspect named; BC_{rate} for energy consumption due to building characteristics, OB_{rate} for energy consumption due to occupancy behaviour and ES_{rate} for the energy source. To develop BC_{rate} an optimum building was designed by analysing and conducting parametric study of 4569 models varying, orientation, window to wall ratios, zone locations, zone sizes, building shape etc.

A questionnaire survey was conducted to obtain the reference values for the occupancy, lighting and other schedules. To develop the ES_{rate}, the sustainability index proposed by Cartelle Barros et al. (2015) was used. All these rates were then normalised to 0-100 scale and combined through weightage factors obtained through a questionnaire results which was based on the perception of the construction industry. The next chapter will discuss the results and analysis of the research.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 General

This chapter presents the results of model simulations and the development of optimum building based on the results of the parametric study. This further includes the questionnaire results and analysis of the general electricity consumer survey and also the solar PV consumer survey. Finally, the development of the energy score with the results of perception survey is discussed and the results of the scale development also described.

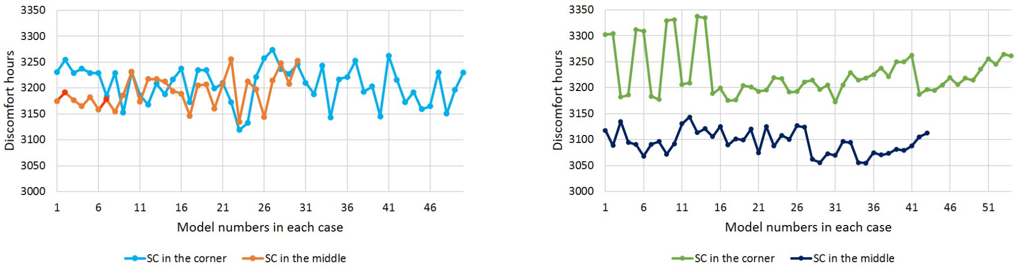
4.2 Effect of building form and zones

The optimisation solutions which had the lowest lighting electricity and lowest discomfort hours of each model was separated and they were plotted against model numbers in each case.

4.2.1 Analysis of the effect of building shape on discomfort hours

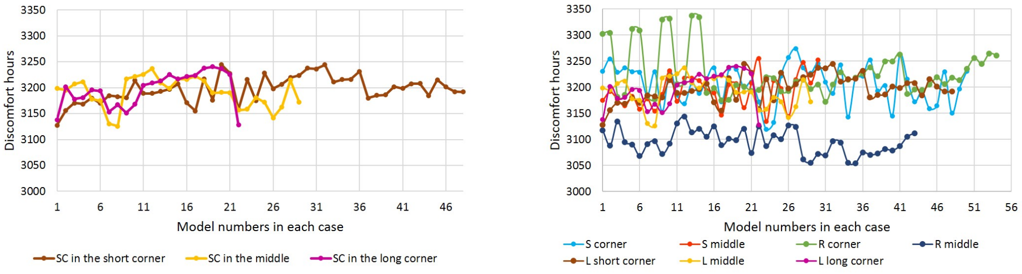
As shown in figure 4.1a, there is no clear difference in the discomfort hours when the position of the staircase changes in square shaped models. As illustrated in figure 3.4a, the staircase was placed at the corner of the house in S case 1 and the staircase was placed in the middle of the house in S case 2 (figure 3.4b). In the rectangular shape, when the staircase is in a corner as shown in figure 3.4c and when the staircase is in the middle (figure 3.4d) a clear difference can be observed in thermal comfort. The Figure 4.1b shows the variation of the discomfort hours with respect to the staircase position in rectangular shaped houses. According to the results a higher thermal comfort can be achieved when the staircase is in the middle of the house than placing it in a corner. Also, while keeping the staircase at the same position, when the zone sizes change, a difference can be observed in thermal comfort.

The locations of the staircase was changed as in the short corner (figure 3.4e), in the middle of the house (figure 3.4f) and in the long corner (figure 3.4g). As indicated in figure 4.1c, there is no clear difference in thermal comfort in L shape cases either when the position of staircase or position of zones relative to staircase changes. However, in L shaped models, a clear difference in thermal comfort can be observed when the zone sizes are changed (figure 4.1c). The overall results based on the house shape is presented in figure 4.1d. This overall result also does not identify a clear pattern or effect when the house shape is changed. However, location of the staircase in rectangular shape houses and zone sizes in all the houses affect the thermal comfort.



(a) Square shape models

(b) Rectangular shape models



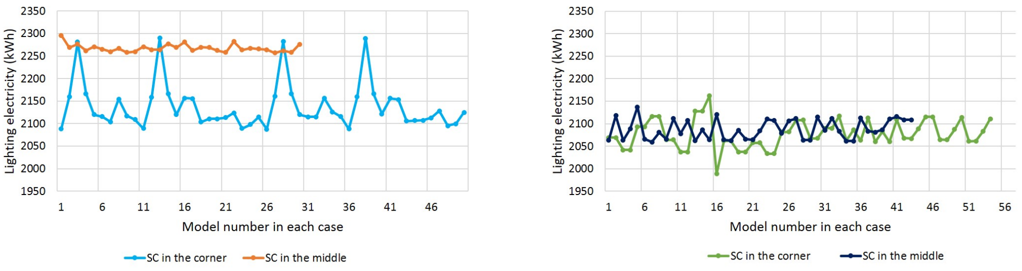
(c) L shape models

(d) Total models

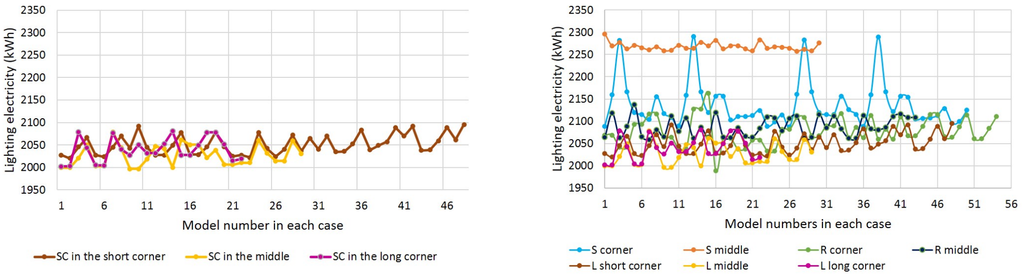
Figure 4.1: Discomfort hours of the model houses based on the position of the staircase

4.2.2 Analysing the effect of building shape on artificial lighting

AS shown in figure 4.2d, the lighting electricity do not have a clear difference for various building shapes except in square shaped models, that the staircase is in the middle (figure 4.2a). When the staircase position changes, in the L shape models (figure 4.2c) and in rectangular shape models (figure 4.2b) only a marginal difference can be observed. As in the case of discomfort hours, some variations can be seen within the cases with the changes in zone sizes and location.



(a) Square shape models (b) Rectangular shape models



(c) L shape models (d) Total models

Figure 4.2: Lighting electricity (kWh) of the model houses based on the position of the staircase

4.2.3 Analysing the effect of zone size and zone location

As discussed in the section 4.2.1 and section 4.2.2, a clear difference was not observed between the cases except in S case 2 for lighting electricity and R case 2 for thermal comfort. However, all these cases showed variations in terms of lighting electricity and thermal comfort when the zone sizes and location changes. Therefore, to properly analyse the effect of zone sizes and locations three size categories were defined for each case and the floor areas of bathroom, kitchen and living in each category is presented in table 4.1. In the zone size 1, the floor area of living was maximum and the floor areas of bathroom and kitchen were minimum in each case. In zone size 2 and zone size 3, floor area of living was decreased and the floor areas of bathroom and kitchen were increased.

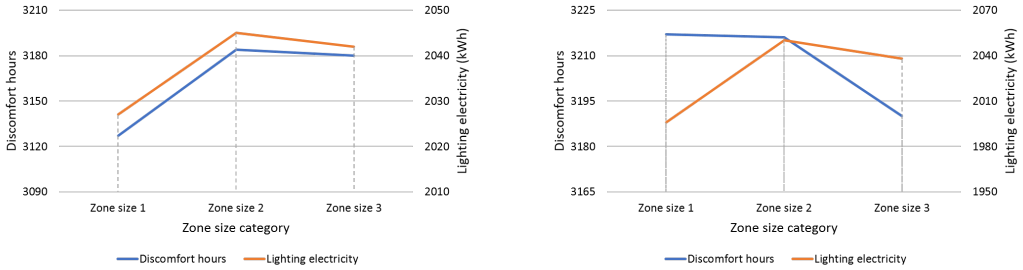
Figure 4.3 presents the variation of the lighting electricity and discomfort hours in three zone sizes in each case. with the change in zone size, the lighting electricity changes up to 3.74% and the discomfort hours changes up to 4.15%. However, the change does not show a clear correlation over the cases and a generalised correlation cannot be observed between lighting electricity and thermal comfort as well. Furthermore, the changing patterns of lighting electricity and thermal comfort within the zone size categories are more case specific and cannot be generalised.

(a) Square shape case 1

(b) Square shape case 2

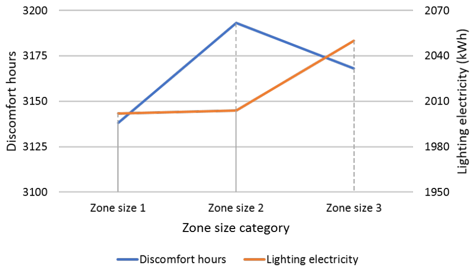
(c) Rectangular shape case 1

(d) Rectangular shape case 2



(e) L shape case 1

(f) L shape case 2



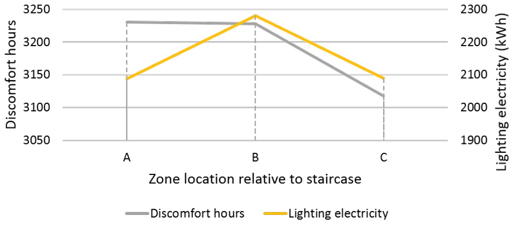
(g) L shape case 3

Figure 4.3: Variation of the thermal comfort and lighting electricity based on the zone size category.

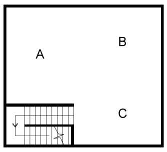
Table 4.1: Floor areas (m^2) of the zones in the three zone size categories

Case	Zone size 1			Zone size 2			Zone size 3		
	Kitchen	Bathroom	Living	Kitchen	Bathroom	Living	Kitchen	Bathroom	Living
S case 1	6.14	2.5	46.92	9.44	3.54	42.64	13.93	5.22	36.33
S case 2	6.05	2.86	46.72	9.87	2.86	43.38	14.78	2.86	38.46
R case 1	5.52	2.52	47.68	7.76	2.52	45.19	11.81	3.36	40.14
R case 2	5.52	2.54	46.97	8.4	4.2	42.16	12.25	4.2	38.17
L case 1	5.52	2.54	46.38	8.04	3.21	42.96	11.85	3.32	38.88
L case 2	5.52	2.54	44.79	8.2	4.38	40.3	12.07	3.34	37.53
L case 3	5.52	2.54	45.09	7.86	2.54	42.82	11.46	4.38	37.23

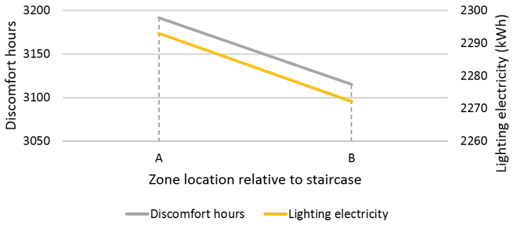
Figure 4.4, 4.5 and 4.6 shows the variation in lighting electricity and discomfort hours when the location of kitchen and bathroom changes relative to the staircase for square shape, rectangular shape and L shape respectively. In the plan layout, the location of zones (kitchen and bathroom) are marked as A, B, C considering whether the zones are placed by the side or away from the location of staircase. When the location of the zone changes, the lighting electricity changes up to 9.24% and the thermal comfort changes up to 2.48%. Similar to the zone size, a clear changing pattern or a correlation between lighting electricity and thermal comfort cannot be observed and the changes are more specific to the relevant case.



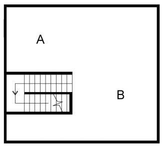
(a) Variation of case 1



(b) Zone locations of case 1

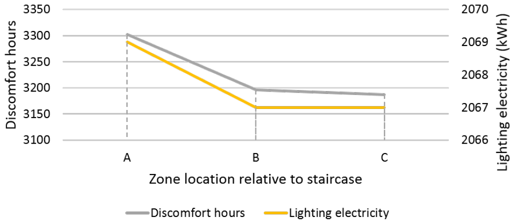


(c) Variation of square shape case 2

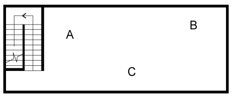


(d) Zone locations of square shape case 2

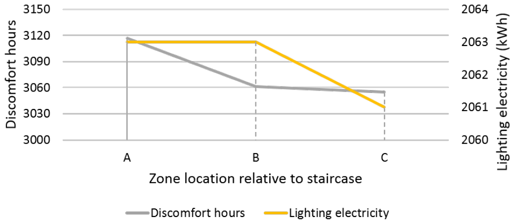
Figure 4.4: Variation of the lighting electricity and thermal comfort based on the zone location in square shape



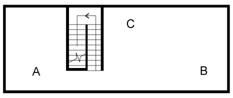
(a) Variation of rectangular shape case 1



(b) Zone locations of rectangular shape case 1



(c) Variation of rectangular shape case 2

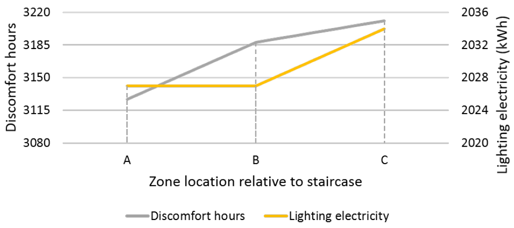


(d) Zone locations of rectangular shape case 2

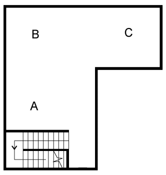
Figure 4.5: Variation of the lighting electricity and thermal comfort based on the zone location in rectangular shape

4.2.4 Analysing the effect of WWR and orientation

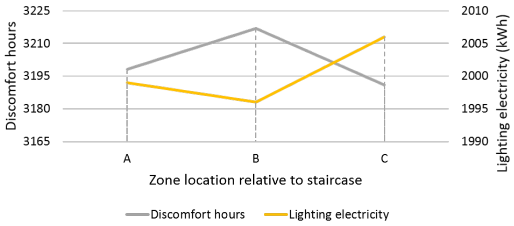
In the previous sections (section 4.2.1 and section 4.2.2), the effect of building shape, zone size, and zone location were analysed only using the best lighting energy and thermal comfort conditions of each model and hence, the effect of orientation and WWR was ignored in analysis. To include the effect of those factors in the analysis, the models in zone size 1 (refer table 4.1 were selected in all cases for further analysis.



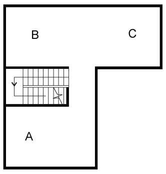
(a) Variation of L shape case 1



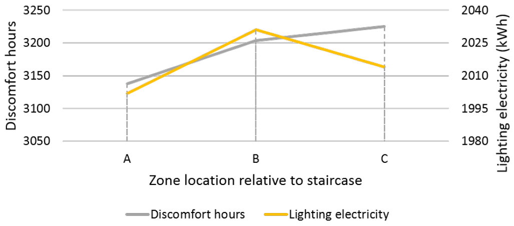
(b) Zone locations of L shape case 1



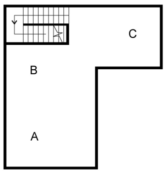
(c) Variation of L shape case 2



(d) Zone locations of L shape case 2



(e) Variation of L shape case 3



(f) Zone locations of L shape case 3

Figure 4.6: Variation of the lighting electricity and thermal comfort based on the zone location in L shape

4.2.4.1 Analysing the effect of WWR

The lighting electricity and discomfort hours results were obtained for the seven models (in seven main cases) varying the WWR as 20, 40, 60 and 80. As indicated in figure 4.7, a positive correlation can be observed between WWR and discomfort hours. The table 4.2 lists the percentage change in discomfort hours compared with the best WWR's discomfort hours. As per the table 4.2, the minimum discomfort hours (best thermal comfort) can be observed in WWR of 20 and in WWR of 40, more than 20% increase in discomfort hours can be observed except in L case 2 (17.8% increase). WWR of 60 increases the discomfort hours by 30 - 40% and in 80 WWR, the increase is 45 - 55% except in L case 2 (41.48% increase). Between the WWRs of 60 and 80, the difference in percentage change is only 10% and between other WWRs, more than 20% can be observed.

Table 4.2: Percentage increase in the discomfort hours of the cases for various orientations compared to the best WWR

Case	S case 1	S case 2	R case 1	R case 2	L case 1	L case 2	L case 3
20	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
40	23.42%	21.08%	21.34%	25.45%	20.67%	17.80%	27.03%
60	40.08%	37.55%	31.29%	43.31%	35.60%	31.78%	43.95%
80	49.81%	47.90%	47.26%	54.58%	45.97%	41.48%	53.30%

As shown in figure 4.8, the minimum lighting electricity (best value) is seen in WWRs of 60 and 80 and between those WWRs, the difference in lighting electricity is nearly zero. The highest lighting electricity value can be observed in WWR of 20 and for square shape and L shape models, the percentage change compared to the best WWR is 1.5 - 3% and in rectangular shape models change is 8.5 - 9.5%.

4.2.4.2 Analysing the effect of orientation

For the same models explained in section 4.2.4.1, the best orientations which provide lowest lighting electricity and best orientation that gives lowest discomfort hours was identified separately for each case and listed in table 4.3. For each case 24 different orientations were obtained by rotating the best orientation by 15^0. For each orientation, the discomfort hours and lighting electricity were obtained and plotted as illustrated in figure 4.9 and figure 4.10. It was identified that, when the models are rotated in 90^0 and 270^0 angles compared to the best orientation, an increase in thermal comfort can be observed.

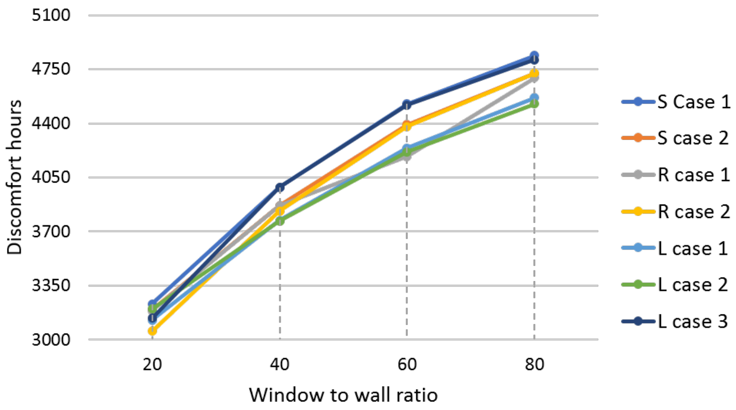


Figure 4.7: Thermal comfort of the cases for various WWR

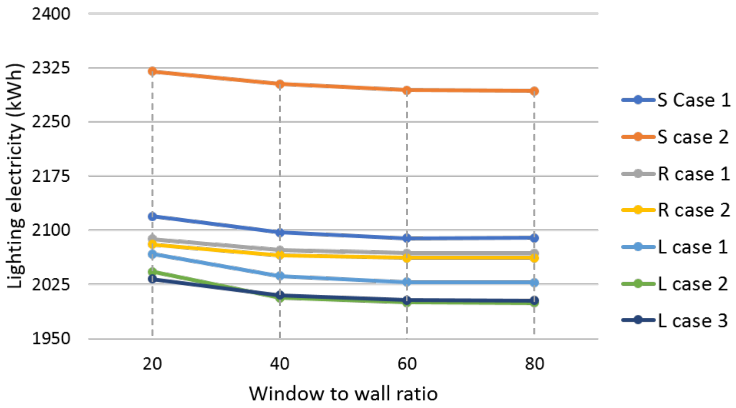


Figure 4.8: Lighting electricity of the cases for various WWR

Table 4.3: Best orientations of the models in terms of minimum discomfort hours and minimum lighting electricity.

Case	S case 1	S case 2	R case 1	R case 2	L case 1	L case 2	L case 3
Discomfort hours	0	270	0	0	60	240	60
Lighting electricity	270	150	90	240	15	0	345

However, in square shape and L shape, the increase is marginal (only 1.5 - 3%) and in rectangular shape, the difference of 8.5 - 9.5% can be seen. As indicated in figure 4.10, the orientation does not have a clear effect on the lighting electricity and for all the orientations and for all the cases, the percentage increase in lighting electricity compared to the best orientation is less than 0.25%.

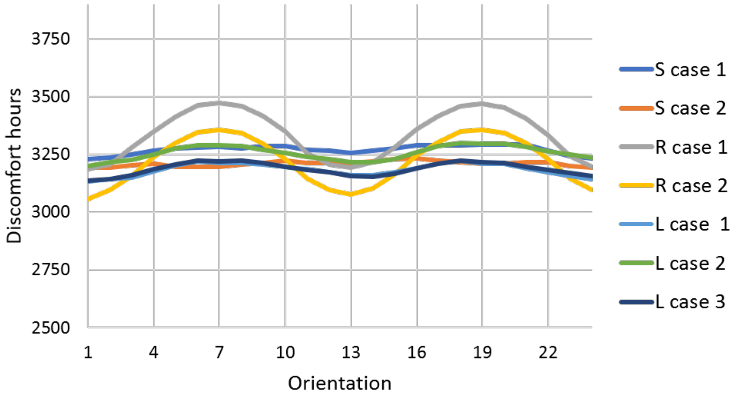


Figure 4.9: Thermal comfort of the cases for various orientations

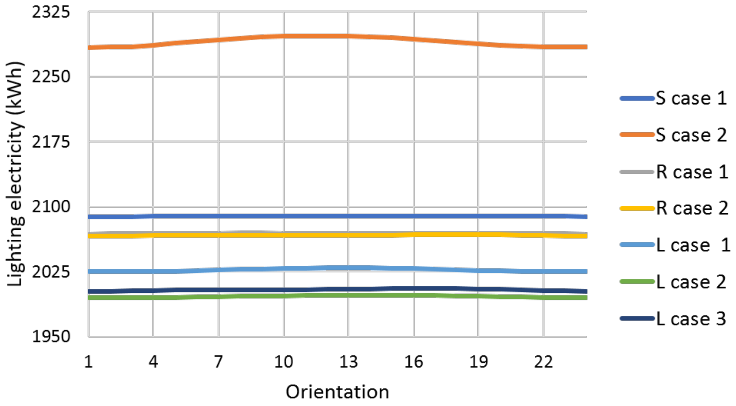


Figure 4.10: Lighting electricity of the cases for various orientations

4.2.5 Discussion

The location of the staircase was regarded as a significant parameter in the case development, mainly due to two reasons. Firstly, as a reference for zone location, the staircase was used and secondly, the staircase location can have several effect on lighting electricity and thermal comfort requirements. According to Edwards (2000), staircases can create stack effect ventilation which can affect the thermal comfort of the models. The stack effect ventilation arises due to vertical air movement. The human activities warm up the cool air inside the building and this warm air passes through vertical elements like ducts and air wells because of the density differences (Aflaki, Mahyuddin, Al-Cheikh Mahmoud, & Baharum, 2015). Stack effect ventilation usually happens in open staircases and the stairways have been considered as exhaust stack in historic buildings Walker (2016).

The best thermal comfort situation for rectangular shape occurs in WWR of

20 and when the staircase is placed in the middle of the house mainly due to the effective use of both cross ventilation and stack ventilation in that scenario. In square shape and L shape, such clear different cannot be observed. However, due to the self-shading effect, L case provides the best thermal comfort when the WWR is increased. This finding validates the work of L. Wang et al. (2007) where, in naturally ventilated residential buildings, the optimum WWR is 24.

In square shape, when the staircase is in the middle of the house, the highest lighting electricity occurs as the staircase block the light and requires higher lighting requirement. Lighting electricity did not have a clear difference (only 1.2 -2.2%) with WWR in this case study mainly due to the occupancy schedules used for the residential buildings. The lighting electricity is required only during the occupancy time, which is usually from evening to morning in the next day and the lighting requirement is compensated by daylight for only few hours.

The zone sizes change the lighting electricity up to 3.74% and thermal comfort up to 4.15%. Further, the location of zones compared to staircase can change lighting electricity up to 9.24% and thermal comfort up to 3.48%. However, either in zone locations or zone sizes, it is difficult to generalise the changing pattern and the pattern is specific to the case. Therefore, to develop a generalized correlation, an analysis by combining multiple factors need to be considered.

4.3 Results of the parametric analysis

Using total energy consumption (TE) as dependent variable and 31 independent variables a parametric analysis was conducted and the results of the first run is presented in table 4.4.Out of these 31 variables 13 variables had to be omitted as they were not significant at 95% confidence level.

Table 4.4: Parametric analysis - first run results

Model	Unstd Coeff (B)	Std Error	Std Coeff (B)	t	Sig
(Constant)	-33.972	258.011	-0.132	0.895	
TBA	8.765	2.501	0.132	3.505	0.000
RA	25.307	8.065	0.160	3.138	0.002
GFKA	-12.634	9.018	-0.059	-1.401	0.161
GFBA	43.618	9.525	0.078	4.579	0.000
GFLA	22.389	8.603	0.339	2.603	0.009
GFBR1A	74.801	13.145	0.694	5.691	0.000
GFBR2A	-8.216	8.286	-0.028	-0.992	0.321
UFBR1A	104.673	12.661	0.971	8.267	0.000
UFBR2A	20.033	2.968	0.124	6.751	0.000
UFBR3A	19.766	2.825	0.098	6.997	0.000
UFCRDA	23.262	2.685	0.234	8.662	0.000
SWA	1.322	2.035	0.038	0.650	0.516
WWA	1.428	3.676	0.041	0.388	0.698
NWA	-4.981	2.198	-0.143	-2.267	0.023
EWA	-0.969	3.660	-0.028	-0.265	0.791
SWIA	12.443	0.802	0.231	15.506	0.000
WWIA	12.250	0.843	0.229	14.525	0.000
NWIA	11.731	0.830	0.212	14.138	0.000
EWIA	7.165	0.895	0.130	8.007	0.000
SCEWNA	-1.991	1.400	-0.014	-1.422	0.155
SCEWEA	-1.141	1.146	-0.010	-0.996	0.319
SCEWSA	-0.819	1.308	-0.006	-0.626	0.531
SCEWWA	-0.675	1.212	-0.006	-0.557	0.578
KEWNA	2.589	1.221	0.023	2.121	0.034
KEWEA	4.517	1.001	0.039	4.510	0.000
KEWSA	0.781	1.215	0.007	0.643	0.520
KEWWA	2.431	0.924	0.021	2.630	0.009
BEWNA	-1.771	1.634	-0.010	-1.084	0.278
BEWEA	-3.276	1.545	-0.018	-2.120	0.034
BEWSA	1.468	1.489	0.008	0.986	0.324
BEWWA	-2.270	1.490	-0.013	-1.523	0.128

As per the analysis following variables were identified as insignificant and omitted during the second run of the parametric analysis.

1. Ground floor kitchen area (GFKA)
2. Ground floor bedroom 2 area (GFBR2A)
3. South faced wall area (SWA)
4. West faced wall area (WWA)
5. East faced wall area (EWA)
6. Staircase - North faced wall area (SCEWNA)
7. Staircase - South faced wall area (SCEWSA)
8. Staircase - West faced wall area (SCEWWA)
9. Staircase - East faced wall area (SCEWEA)
10. Kitchen - South faced wall area (KEWSA)
11. Bathroom - North faced wall area (BEWNA)
12. Bathroom - South faced wall area (BEWSA)
13. Bathroom - West faced wall area (BEWWA)

Second parametric run was based on 18 parameters and the results are shown in table 4.5.Out of these 18 variables 17 variables were identified as significant at 95% confidence level.

Table 4.5: Parametric analysis - second run results

Model	Unstd (B)	Coeff	Std Error	Std Coeff (B)	t	Sig
(Constant)	72.983		137.045	0.533	0.594	
TBA	8.992		2.454	0.135	3.663	0.000
RA	16.835		2.739	0.106	6.147	0.000
GFBA	52.010		3.811	0.093	13.649	0.000
GFLA	33.162		1.338	0.502	24.784	0.000
GFBR1A	80.003		8.292	0.742	9.648	0.000
UFBR1A	98.846		8.437	0.917	11.715	0.000
UFBR2A	20.104		2.834	0.124	7.094	0.000
UFBR3A	20.046		2.731	0.099	7.341	0.000
UFCRDA	22.971		2.625	0.231	8.751	0.000
NWA	-3.883		0.502	-0.112	-7.735	0.000
SWIA	12.312		0.735	0.229	16.746	0.000
WWIA	12.489		0.810	0.234	15.425	0.000
NWIA	11.590		0.779	0.210	14.869	0.000
EWIA	7.123		0.847	0.129	8.406	0.000
KEWNA	1.526		0.697	0.013	2.190	0.029
KEWEA	4.201		0.883	0.036	4.757	0.000
KEWWA	1.968		0.845	0.017	2.330	0.020
BEWEA	-1.620		1.235	-0.009	-1.311	0.190

The east faced external wall area of bathroom (BEWEA) was identified as insignificant and was omitted in the third run of the parametric analysis.

1. Total area of the building (TBA)
2. Roof area (RA)
3. Ground floor bathroom area (GFBA)
4. Ground floor living area (GFLA)
5. Ground floor bedroom 1 area (GFBR1A)
6. First floor bedroom 1 area (UFBR1A)
7. First floor bedroom 2 area (UFBR2A)
8. First floor bedroom 3 area (UFBR3A)
9. First floor corridor area (UFCRDA)
10. North faced wall area (NWA)
11. South faced window area (SWIA)
12. West faced window area (WWIA)
13. North faced window area (NWIA)
14. East faced window area (EWIA)
15. Kitchen - North faced wall area (KEWNA)
16. Kitchen - East faced wall area (KEWEA)
17. Kitchen - West faced wall area (KEWWA)

The results of the third parametric analysis with 17 independent variables is shown in table 4.6. In the third run, all the independent variables were significant. All the following significant variables were considered when developing the optimal house.

Table 4.6: Parametric analysis - third run results

Model	Unstd (B)	Coeff	Std Error	Std Coeff (B)	t	Sig
(Constant)	82.335		136.871	0.602	0.548	
TBA	9.038		2.454	0.136	3.682	0.000
RA	16.669		2.736	0.105	6.092	0.000
GFBA	51.898		3.810	0.093	13.622	0.000
GFLA	33.184		1.338	0.503	24.801	0.000
GFBR1A	79.854		8.292	0.741	9.631	0.000
UFBR1A	98.782		8.438	0.916	11.707	0.000
UFBR2A	20.022		2.834	0.124	7.066	0.000
UFBR3A	20.188		2.729	0.100	7.398	0.000
UFCRDA	23.005		2.625	0.231	8.764	0.000
NWA	-3.816		0.499	-0.110	-7.640	0.000
SWIA	12.342		0.735	0.230	16.792	0.000
WWIA	12.738		0.787	0.238	16.184	0.000
NWIA	11.543		0.779	0.209	14.823	0.000
EWIA	6.908		0.831	0.125	8.309	0.000
KEWNA	1.635		0.692	0.014	2.362	0.018
KEWEA	3.867		0.846	0.033	4.573	0.000
KEWWA	1.936		0.844	0.017	2.293	0.022

The regression variable plots of the significant variables are available in figure 4.11 to figure 4.13.

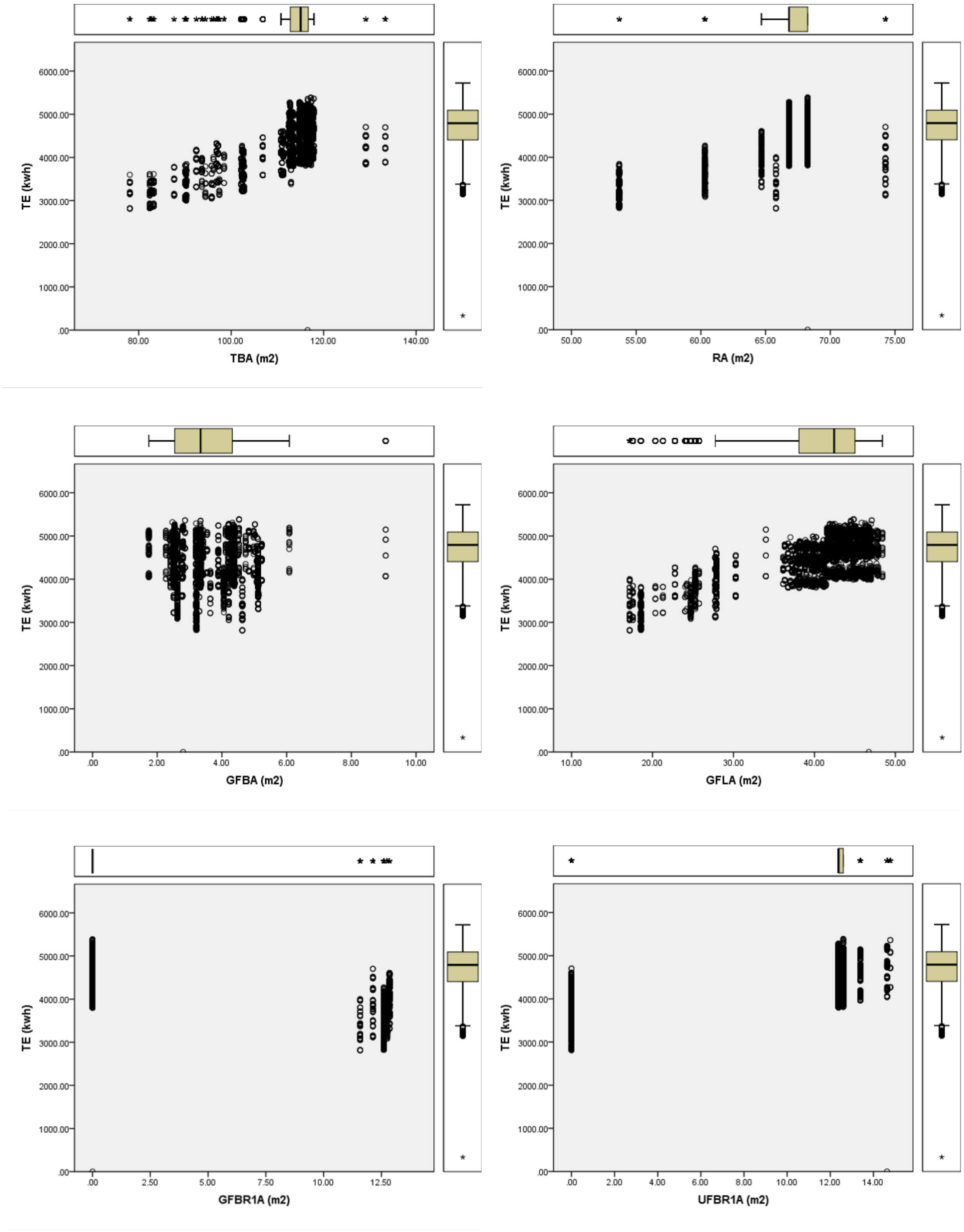


Figure 4.11: Regression plots of significant variables (TBA, RA, GFBA, GFLA, GFBR1A, UFBR1A

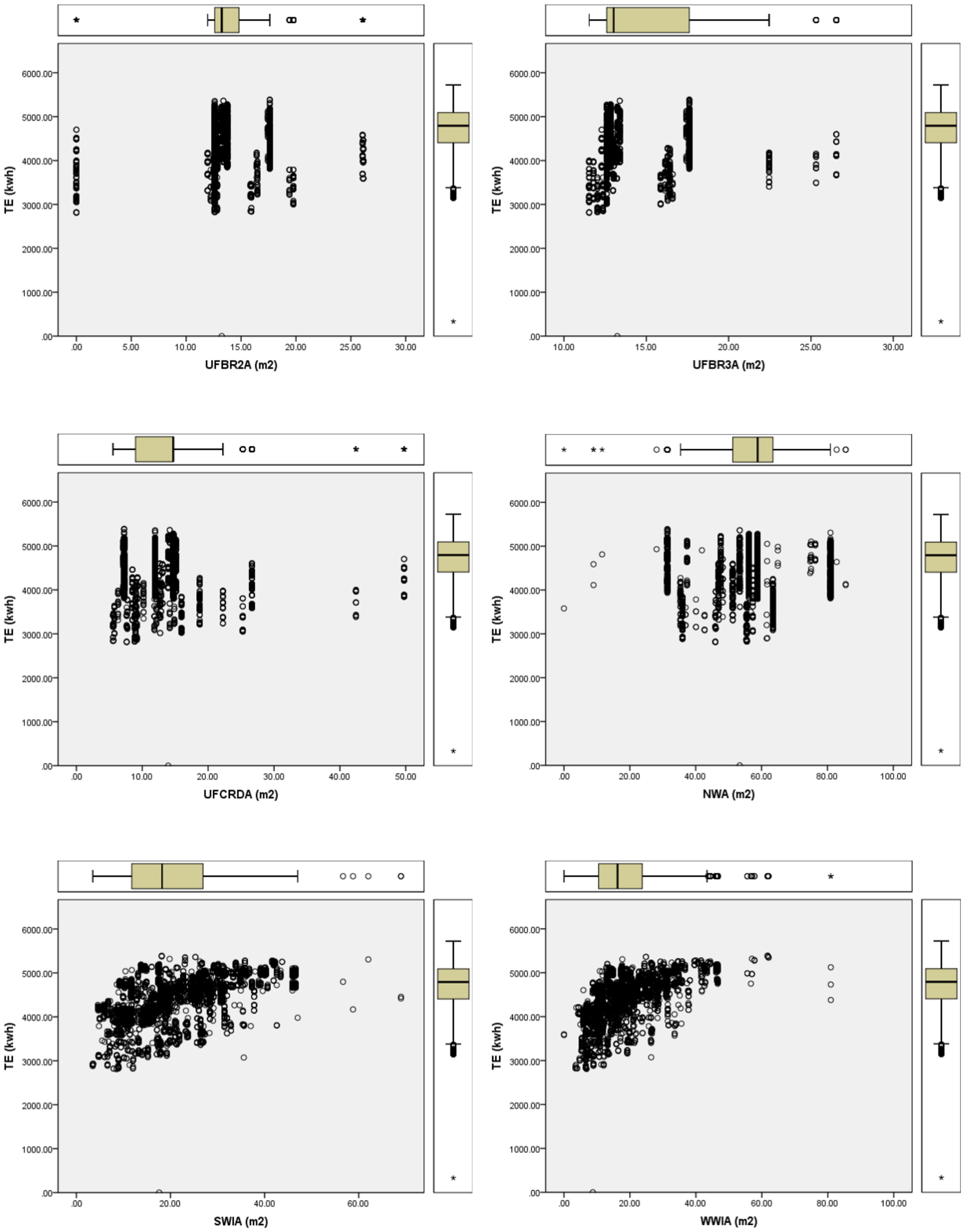


Figure 4.12: Regression plots of significant variables (UFBR2A, UFBR3A, UFCRDA, NWA, SWIA, WWIA

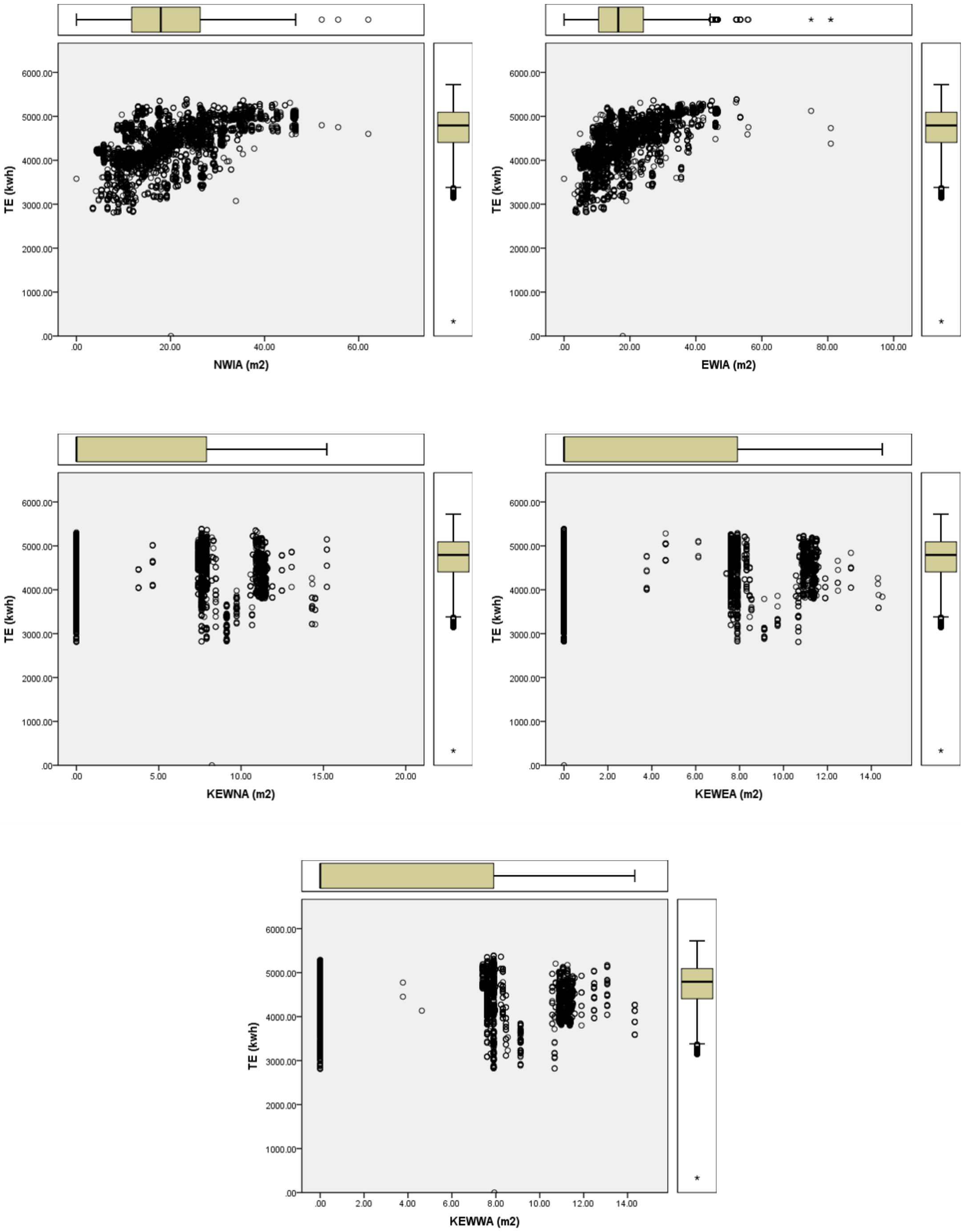


Figure 4.13: Regression plots of significant variables (NWIA, EWIA, KEWNA, KEWEA, KEWWA

4.4 Optimum building design

The parametric analysis results indicated certain conditions to be considered during optimum house design. the following conditions were added as constraints in the design process. The following conditions were added as constraints in the design process.

- Total building area should be minimum
- Roof area should be minimum
- Bathroom area should be minimum
- Bedroom area should be minimum
- First floor bedroom areas should be minimum
- First floor corridor area should be minimum
- North faced wall area should be high
- Window areas facing each direction should be minimum
- Avoid placing kitchen walls facing east
- Ground floor first bedroom area should be minimum

According to those conditions a house model was prepared with flat roof and no shadings. In this model, the zones were arranged so that the total building area is minimum, and the roof area is minimum. Further, the minimum dimensions allocated by urban development authority was used for bathroom, bedrooms, and kitchen (refer table 3.5. Corridor areas were kept minimum and the rooms were arranged mainly having wall areas in north direction. The window areas were minimised ensuring the urban development authority regulations were met as indicated in table 3.6. The kitchen was moved to west so that the kitchen walls are not facing east direction.

The materials used for this model was similar to those which were used for the models prepared for parametric analysis. Prepared initial model is presented in figure 4.14 and the plan views are shown in figure 4.15.

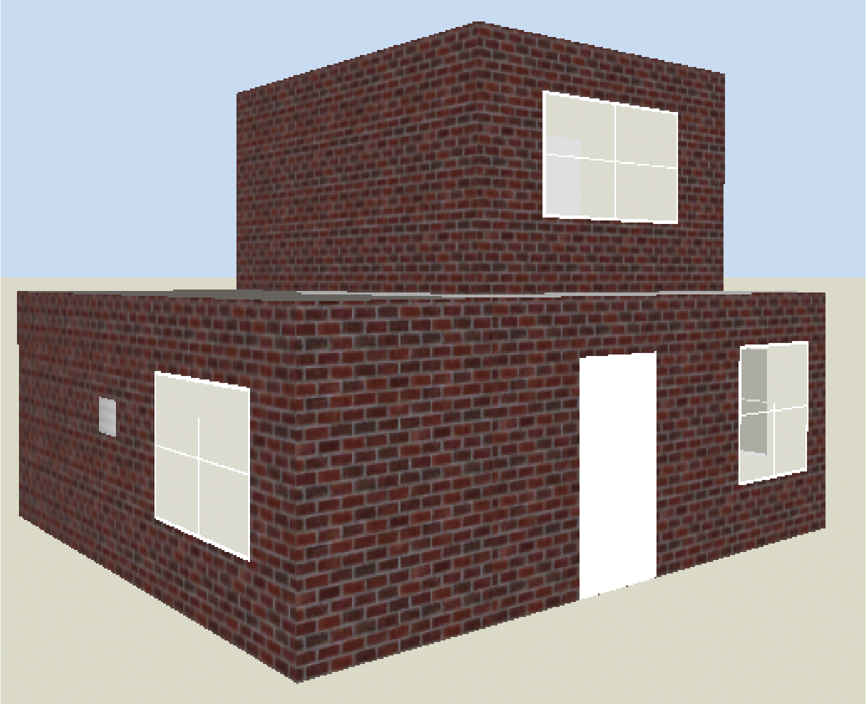
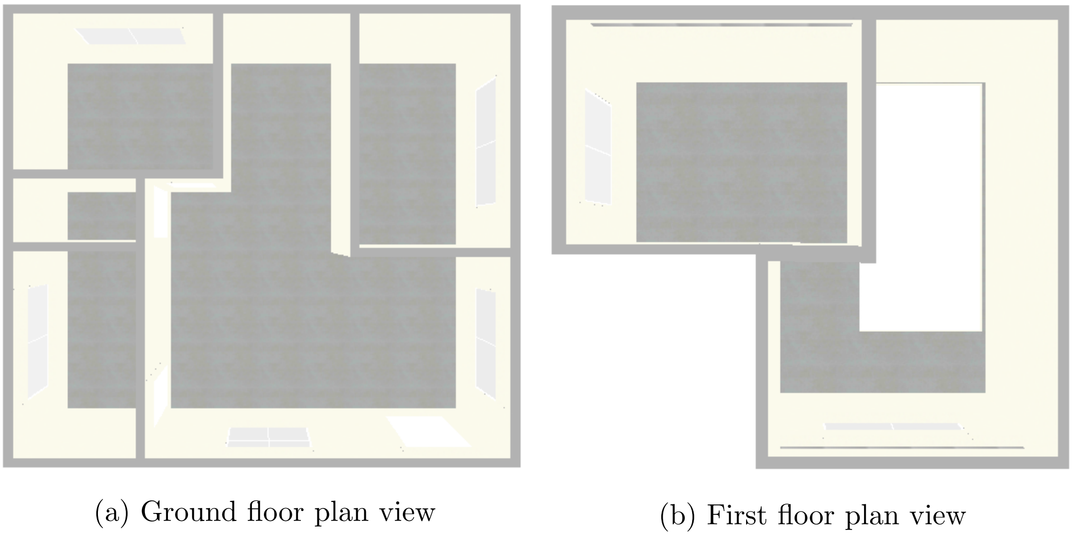


Figure 4.14: Initial model prepared for optimal model



(a) Ground floor plan view

(b) First floor plan view

Figure 4.15: Plan views of the initial model

The simulation was run for one year keeping same activity and other templates used in the models used for parametric analysis. This resulted lighting electricity of 1178.607 kwh and 2977 discomfort hours (ASHRAE adaptive comfort 80% acceptability). This result was less than the minimum values received for the parametric analysis models. After deciding the optimal form, several modifications for the model was done, maintaining the same zone layout, orientation and window to wall ratios. The flat roof was changed to a pitch roof including clay tiles as materials which reduced the thermal discomfort hours to 1075. Further, window shades, eves, vents were added and the floor material was changed to ceramic tiles. The walling material was changed to burnt brick, plastered and painted both sides. These changes reduced the discomfort hours to 148 and the lighting energy was reduced to 1153 kwh. The modified optimum model is shown in figure 4.16.

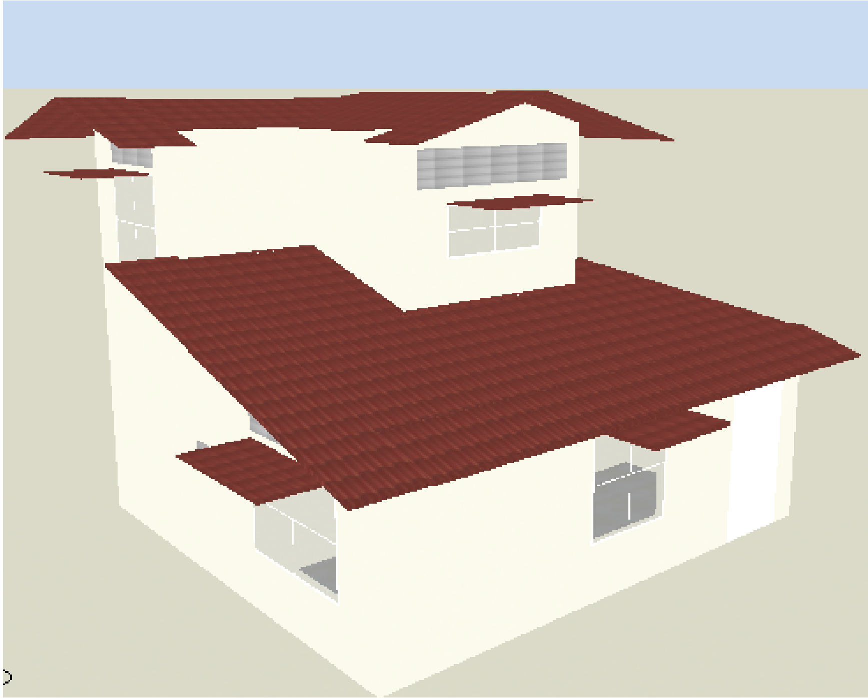


Figure 4.16: Optimum house model

This 148 discomfort hours for one year period was obtained for the optimal models without introducing additional air speeds. As discussed in chapter 2 section 2.3, the acceptable operative temperature limits increase with the average air speed introduced as indicated in table 4.7.

Table 4.7: Increase in acceptable operative temperature limits resulting from increased air velocity in occupant controlled naturally ventilated spaces (Eddy et al., 2017).

	Average air speed		
	0.6 m/s (118 fpm)	0.9 m/s (177 fpm)	1.2 m/s (236 fpm)
Operative temperature limit increase	1.2^0C	1.8^0C	2.2^0C

Since the model has been prepared for a tropical climate, only the upper limit of the acceptable operative temperature is valid for calculations. However, this comfort condition can be further improved by introducing additional air velocities by means of fans. This was used to calculate the total energy required for thermal comfort in the optimal model building.

4.4.1 Calculating the total energy consumption of the optimum model

Calculating the thermal comfort energy for each day in the year is time consuming and it is not practical in the future actual energy rating scenarios as well. Therefore, the thermal comfort energy was only obtained for the hottest day in the hottest month. Table A.1 (appendix A) shows the average monthly outdoor temperature in the weather file and this indicate May as the hottest month. As shown in table A.2 in appendix A, the hottest day in May is 22^{nd}. Therefore, for the thermal comfort calculations, 22^{nd} may was taken as the hottest day. table A.2

The upper 80% acceptability limit for operative temperature can be calculated using the equation 4.1 (Eddy et al., 2017).

$$\text{Upper 80\% acceptability limit } (^{0}C) = 0.31\overline{t_{pma(out)}} + 21.3 \tag{4.1}$$

For the equation 4.1, the prevailing mean outdoor temperature $\overline{t_{pma(out)}}$ need to be calculated. For that, the average of the daily means were calculated. The daily mean was calculated by taking the average of minimum and maximum temperatures of each day in May (Refer table A.2 in A). As per the calculation, $\overline{t_{pma(out)}}$ was $28.47^{0}C$. Using equation 4.1, the 80% acceptable operative temperature limits were calculated and the results are shown in the table 4.8.

Table 4.8: Calculated acceptable operative temperature limits

Air speed	Upper 80% acceptable limits(^{0}C)	Upper 90% acceptable limits(^{0}C)
0.3	30.13	29.13
0.6	31.33	30.33
0.9	31.93	30.93
1.2	32.33	31.33

To convert the air velocities to energy terms, it is required to identify the energy required for a ceiling fan to provide those velocities. According to a research carried out by (Sonne & Parker, 1998), the ceiling fan operating at low speed create air velocities nearly 0.25 - 0.55 m/s, and at medium and high speed create 0.55 - 1.25 m/s and 1.15-2.05m/s air velocities respectively. To take the average air velocities and to match the air speed to achieve 80% acceptable limits, the fan speeds indicated in table 4.9 was used. The table further shows the power (Watts) required for the ceiling fan to operate at low, medium and high speeds.

Table 4.9: Air velocities and fan power at different fan speeds

Air velocity required (m/s)	Fan speed	Fan power required (Watts)
0.3	Low	9
0.6	Medium	27
0.9	Medium	27
1.2	High	75

For each hour, the required velocities to achieve 90% acceptable limits and 80% acceptable limits of operative temperature for each hour in May 22^{nd} were identified and presented in table B.1. According to the table B.1, 67% of the time, the optimum house can achieve 80% acceptable limits without introducing additional air speeds. And 33% of the time this can be achieved by having 0.6 m/s velocity which can be obtained by ceiling fan operated at medium speed. Therefore, this model was taken as the optimum model for the energy rating calculations.

However, for the optimum energy calculations more accurate values are required and hence, the operative temperature of each zones (which can operate fans) were considered in the final calculations. Table 4.10 shows the number of hours that fall in to various operative temperature categories in each zone for the optimum model.

To calculate the fan power, $29 \leq$ operative temperature < 30 was taken as low speed fans, $30 \leq$ operative temperature < 32 was taken as medium speed fans and $32 \leq$ operative temperature < 32.4 was taken as high speed. The kitchen and three bedrooms can be cooled with one fan per room. However, the floor area of the living is nearly 14 m^2 (according to equation 3.8. Therefore, two ceiling cans were used for living area in the calculation. According to those considerations, the optimum house requires 20.5 hours of low speed fan hours, 20 hours of medium speed fan hours and 2 hours of high speed fan hours for all the zones. Hence, in total 0.87kWh is required for the hottest day in May (22^{nd} May) to achieve

Table 4.10: Number of hours in operative temperature categories

Zone	Operative temperature category						
	26.00≤ 27.00>	27.00≤ 28.00>	28.00≤ 29.00>	29.00≤ 30.00>	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Kitchen	0	2.5	6	3	2.5	0	0
Living	0	0	8	3.5	2.5	0	0
Bedroom1	0	3	5	3	3	0	0
Bedroom2	0	4.5	4.5	4	1	0	0
Bedroom3	0	0	0	3.5	5.5	3	2

the thermal comfort. For lighting, 2.98kWh is required and in total 3.85kWh is needed to achieve cooling and lighting requirements for 22^{nd} May.

4.4.2 Calculating the total energy consumption of the optimum air conditioned models

For the air conditioned buildings, same optimum model used for the naturally ventilated building was used. The air conditioned space can be different from building to building and the optimum energy requirement should be different for those configurations. Therefore, six cases were designed and modeled to get the energy requirement for those configurations as follows.

Case 1: One bedroom is air conditioned

Case 2: Two bedrooms are air conditioned

Case 3: Three bedrooms are air conditioned.

Case 4: One bedroom and living area are air conditioned

Case 5: Two bedrooms and living area are air conditioned

Case 6: Three bedrooms and living area are air conditioned

For each case, the number of hours that fall into operative temperature categories in each zone was obtained through simulations and is presented in table 4.11 to 4.16. The calculated energy requirements for each case is presented in table 4.17.

Table 4.11: Number of hours in operative temperature categories in air conditioned case 1

Zone	Operative temperature category						
	26.00≤ 27.00>	27.00≤ 28.00>	28.00≤ 29.00>	29.00≤ 30.00>	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Kitchen	0	3	5.5	3	2.5	0	0
Living	0	0.5	8	3	2.5	0	0
Bedroom2	0	4.5	4.5	4	1	0	0
Bedroom3	0	0	0	3.5	5.5	3.5	1.5

Table 4.12: Number of hours in operative temperature categories in air conditioned case 2

Zone	Operative temperature category						
	26.00≤ 27.00>	27.00≤ 28.00>	28.00≤ 29.00>	29.00≤ 30.00>	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Kitchen	0	3	5.5	3	2.5	0	0
Living	0	2.5	6	3	2.5	0	0
Bedroom3	0	0	0	4.5	5	3	1.5

Table 4.13: Number of hours in operative temperature categories in air conditioned case 3

Zone	Operative temperature category						
	26.00≤ 27.00>	27.00≤ 28.00>	28.00≤ 29.00>	29.00≤ 30.00>	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Kitchen	0	3.5	5	3	2.5	0	0
Living	0	3	6	3	2	0	0

Table 4.14: Number of hours in operative temperature categories in air conditioned case 4

Zone	Operative temperature category						
	26.00≤ 27.00>	27.00≤ 28.00>	28.00≤ 29.00>	29.00≤ 30.00>	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Kitchen	0	4.5	4.5	3	2	0	0
Bedroom2	0	6.5	3.5	4	0	0	0
Bedroom3	0	0	0	6	4	3	1

Table 4.15: Number of hours in operative temperature categories in air conditioned case 5

Zone	Operative temperature category						
	26.00≤ 27.00>	27.00≤ 28.00>	28.00≤ 29.00>	29.00≤ 30.00>	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Kitchen	0	4.5	4.5	3.5	1.5	0	0
Bedroom3	0	0	0	7.5	2.5	3.5	0.5

Table 4.16: Number of hours in operative temperature categories in air conditioned case 6

Zone	Operative temperature category						
	26.00≤ 27.00>	27.00≤ 28.00>	28.00≤ 29.00>	29.00≤ 30.00>	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Kitchen	0	5	4	3.5	1.5	0	0

Table 4.17: Energy consumption of optimum air conditioned cases

Cases	Energy consumption (kWh)		
	Fans	Air conditioning and lighting	Total
AC case 1	0.7335	12.11	12.8435
AC case 2	0.6525	19.55	20.2025
AC case 3	0.2565	32.65	32.9065
AC case 4	0.435	44.18	44.615
AC case 5	0.339	50.82	51.159
AC case 6	0.072	62.82	62.892

4.4.3 Calculating energy consumption for actual naturally ventilated house

For calculating the energy consumption for actual houses, the same method followed in optimum house is used. As shown in figure 4.17, firstly the actual house is simulated for 22^{nd} May. Then for the hours which are comfortable with 90% acceptability at 0.3m/s, then only the natural ventilation is used for that period. If not, it is checked whether the zones are comfortable with 80% acceptability at 0.3m/s and fans at low speed is used for those hours. If it is not comfortable, then it is required to check whether the house is comfortable with 80% acceptability at 0.9m/s and allocate the fans at medium speed for those hours. If still the comfort conditions are not met, then comfortability with 80% acceptability at 1.2m/s is checked and fans at high speed are allocated for those hours. If all of these are not met then air conditioning should be used for the unmet hours.

For the case study climate conditions (Katunayake), the decision making can be done easily by giving the temperature ranges related to various comfort conditions given in figure 4.17. As illustrated in figure 4.18, if the operative temperature of the house is less than 29^0C, only natural ventilation is used. If the operating temperature is higher than or equal to 29^0C and less than 30^0C, then fans are used at low speed. Similarly, if the operating temperature is greater than or equal to30^0C and less than 32^0C, then fans are used at medium speed and if the temperature is higher equal to 32^0C and less than 32.4^0C, then fans at high speed will be used. If all those comfort conditions are not met, air conditioning has to be used as discussed earlier.

To calculate the energy consumption for the air conditioned time period, the unmet zones will be changed from natural ventilation to air conditioning (split + mechanical ventilation). The set point temperature will be kept at 32.33^0C, where the air conditioning will be only used if the operating temperature exceed the set point temperature. This energy consumption for cooling with air conditioning is added to get the total energy consumption of the actual house. Therefore, the total electricity consumption for actual house is calculated as shown in equation 4.2 where, E_{actual} is the electricity consumption of the actual house, $E_{lighting}$ is the electricity consumed for lighting in May 22^{nd}, E_{fans} is the electricity for fans in 22^{nd} May, and E_{AC} is the electricity for air conditioning in 22^{nd} May.

$$E_{actual} = E_{lighting} + (E_{fans} + E_{AC}) \tag{4.2}$$

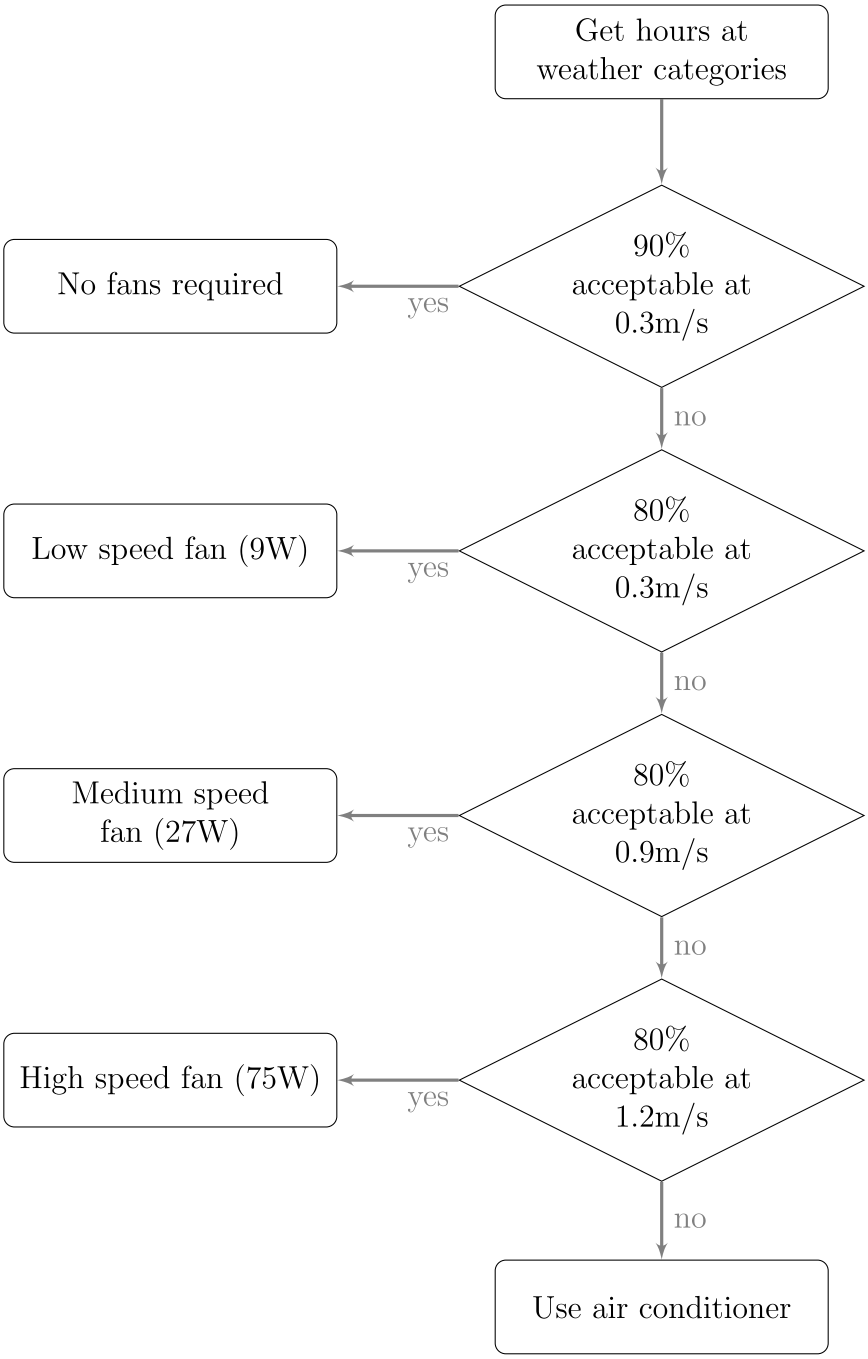


Figure 4.17: Decision process for calculating the energy required to provide thermal comfort in actual houses

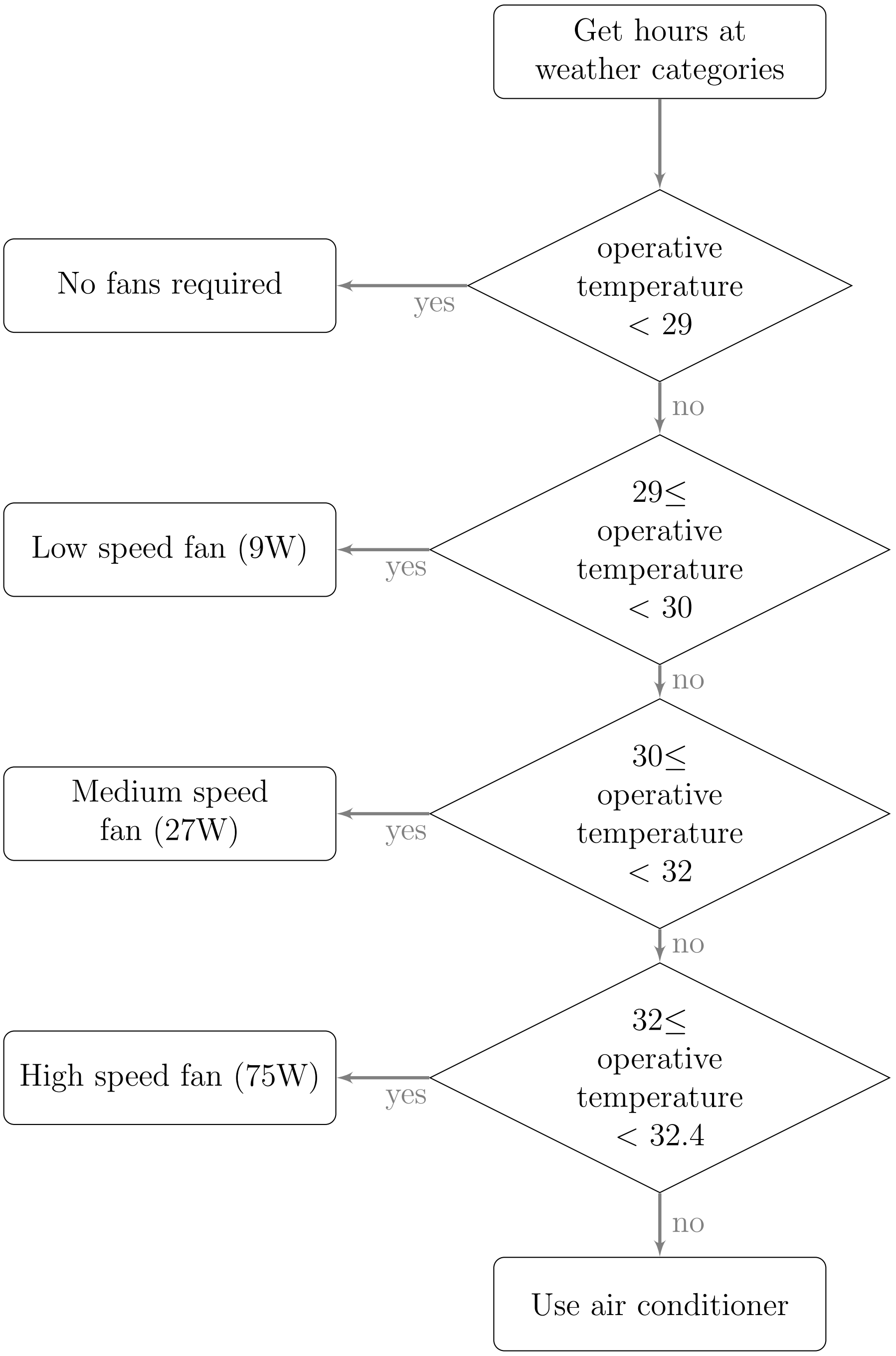


Figure 4.18: Decision process for calculating the energy required to provide thermal comfort in actual houses in the case study climatic conditions

4.5 Effect of occupant behaviour on energy efficiency

To analyse the effect of occupant behaviour on energy efficiency in Sri Lanka a questionnaire survey was conducted focusing the domestic consumers. The results of the consumer survey is mainly discussed in this section.

4.5.1 Results of the consumer energy survey

Out of the 390 received filled questionnaires, only 336 were selected for the analysis after removing the incomplete data. The respondents were from different districts in Sri Lanka and the houses with various shapes could be covered. The distribution of the responds based on the district and building shape is presented in table 4.18.

Table 4.18: Distribution of the respondents based on district and building shape

District	% of respondents	Shape	% of respondents
Gampaha	17.26%	R shape	54%
Colombo	16.37%	S shape	22%
Galle	10.71%	L shape	9%
Mathara	9.82%	T shpate	2%
Kaluthara	7.44%	Other	13%
Kurunegala	7.44%		
Hambanthota	6.85%		
Jaffna	5.36%		
Rathnapura	3.57%		
Kegalle	2.68%		
Anuradhapura	2.08%		
Kandy	2.08%		
puttlum	1.49%		
Ampara	1.19%		
Monaragala	1.19%		
Badulla	0.89%		
Batticaloa	0.89%		
Mulathivu	0.60%		
Nuwaraeliya	0.60%		
Polonnaruwa	0.60%		
Trincomalee	0.60%		
Kilinochchi	0.30%		

Number of respondents in various age categories is presented in figure 4.19 and number of respondents in employment categories (Employed, student, stay at home) is presented in figure 4.20. Distribution of the households based on the number of occupants, number of floors and number of bedrooms are shown in figure 4.21, figure 4.22 and figure 4.23 respectively. Average electricity consumption of the households are presented in figure 4.24 and the ventilation and cooling methods of the respondents are shown in figure 4.25.

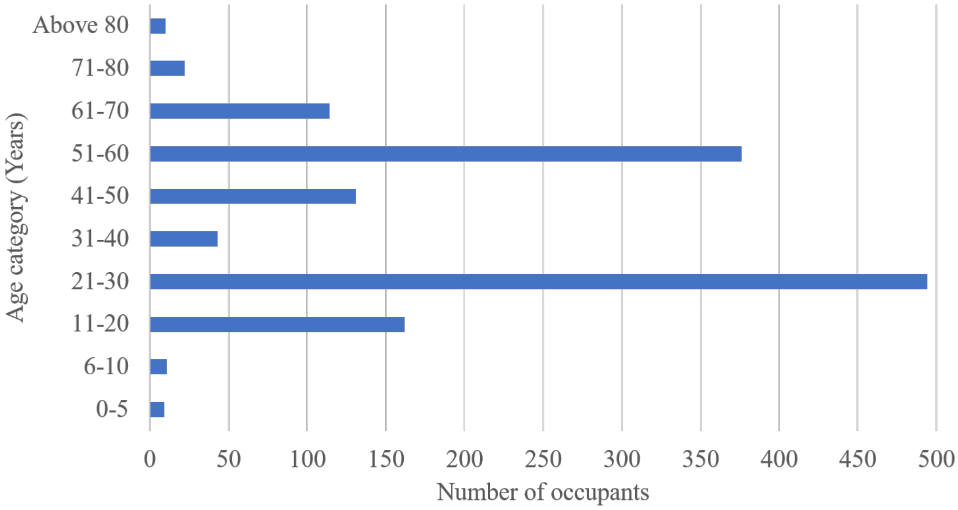


Figure 4.19: Number of occupants in age categories

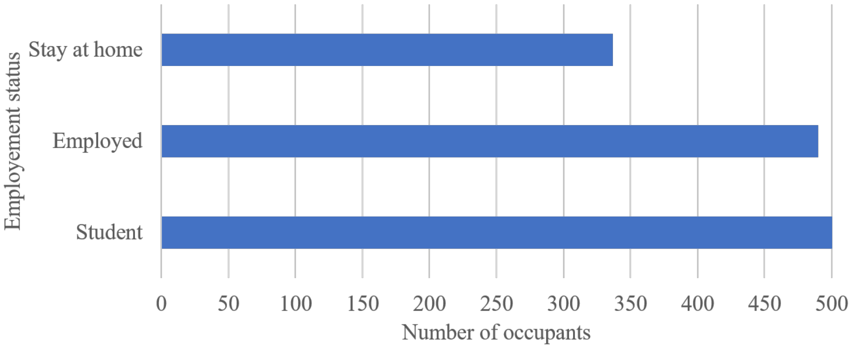


Figure 4.20: Number of occupants in employment categories

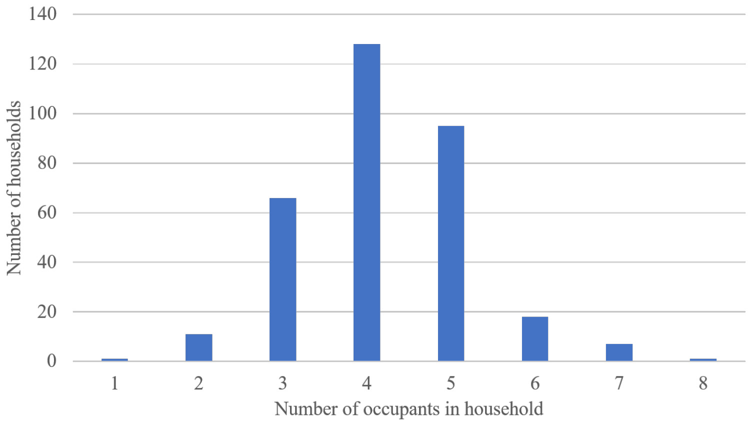


Figure 4.21: Number of households based on number of occupants in households

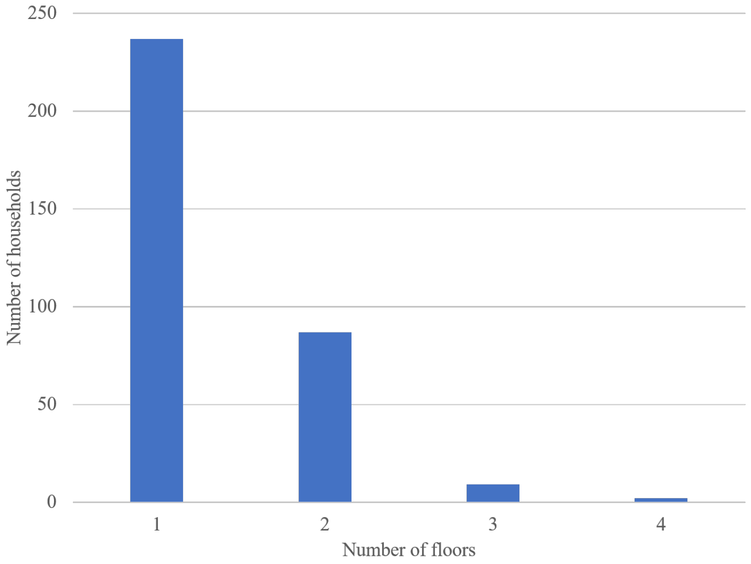


Figure 4.22: Number of households based on number of floors

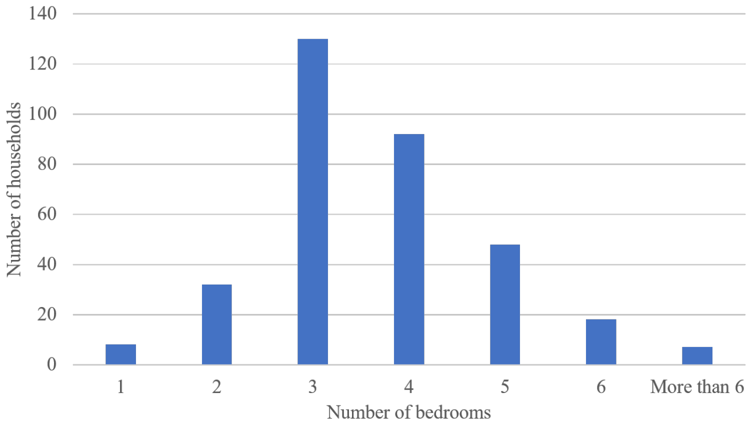


Figure 4.23: Number of households based on number of bedrooms

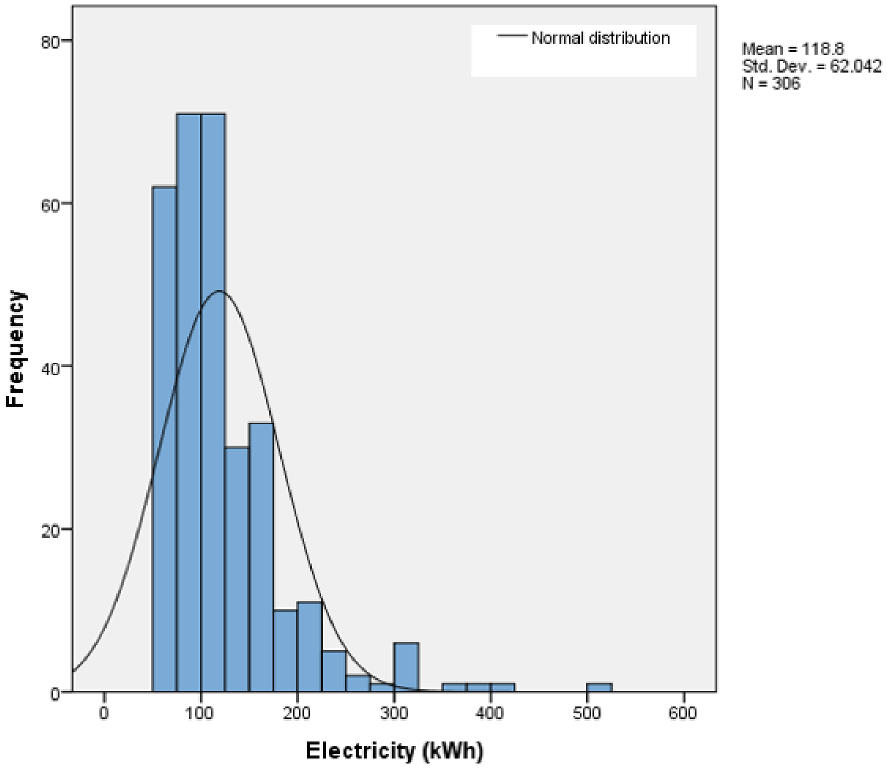


Figure 4.24: Average electricity consumption of the households

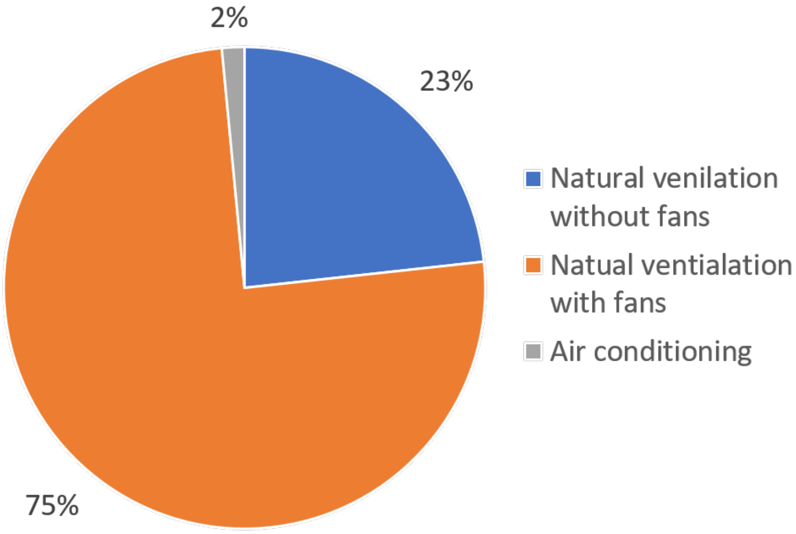


Figure 4.25: Ventilation and cooling methods of respondents

Figure 4.26 and figure 4.27 show the average occupancy schedules (leave home and return home) of the respondents in weekdays, Saturdays and Sundays. In weekdays, 41% of the respondents leave home at 7.00 AM and 55% return home during 5.00 - 6.00 PM. In Saturdays 20% stay at home and 55% leave home before 7.00 - 8.00 AM. In Sundays 30% stay at home and 38% leave home between 7.00 - 8.00 AM. However, there is no clear pattern on the returning time in week ends.

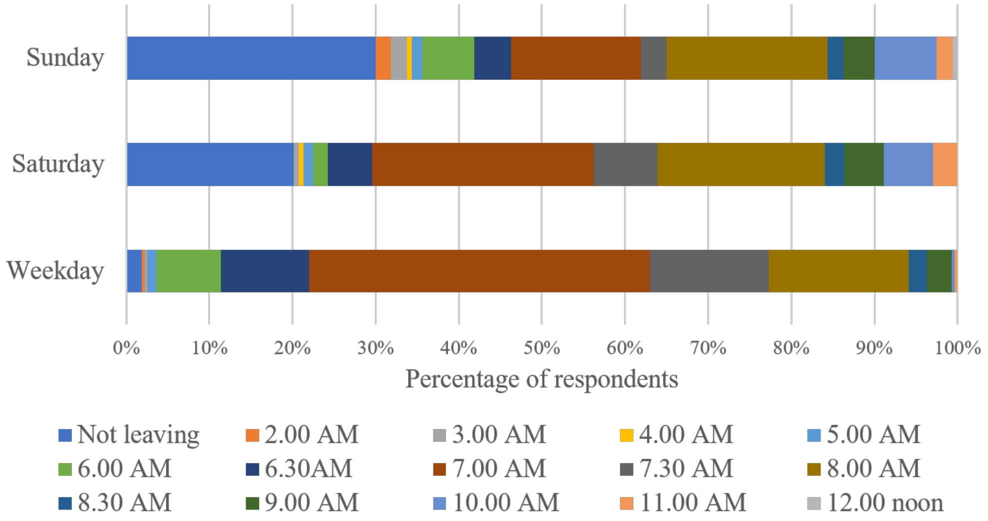


Figure 4.26: Occupancy schedule - Time of leaving home

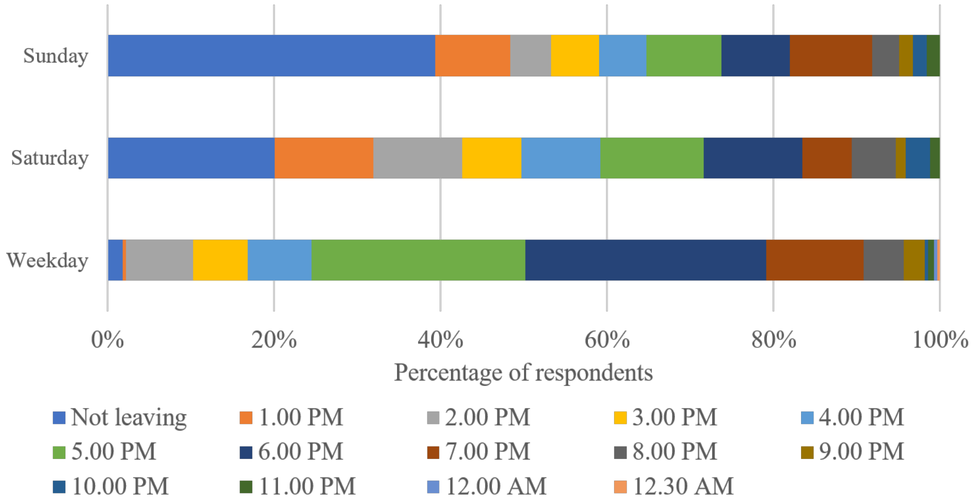


Figure 4.27: Occupancy schedule - Time of returning home

The average door opening schedules of the respondents are presented in figure 4.28 and window opening schedules are presented in figure 4.29. According to the results 12.8% of the respondents do not keep the door open and when considering the rest of the households, 80% open the door between 6.00 AM to 7.00 AM and closing time varies from 6.00 PM to 10.00 PM where, 23% of the respondents close the door at 6.00 PM. Fifteen percent of the households keep the windows open always and from the rest of the respondents 40% open the window at 6 AM and 40% close the window at 7.00 PM.

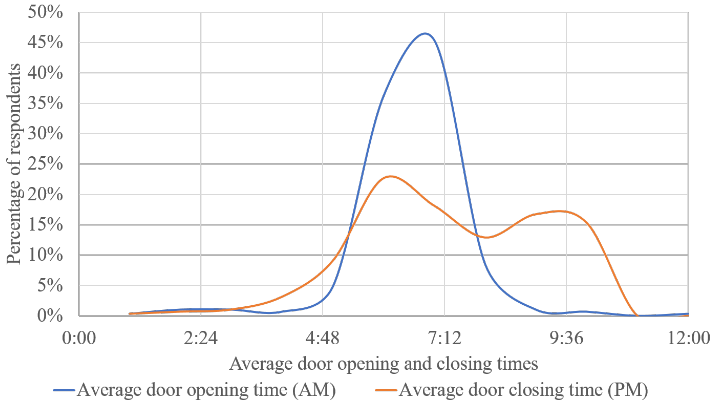


Figure 4.28: Average door opening schedules

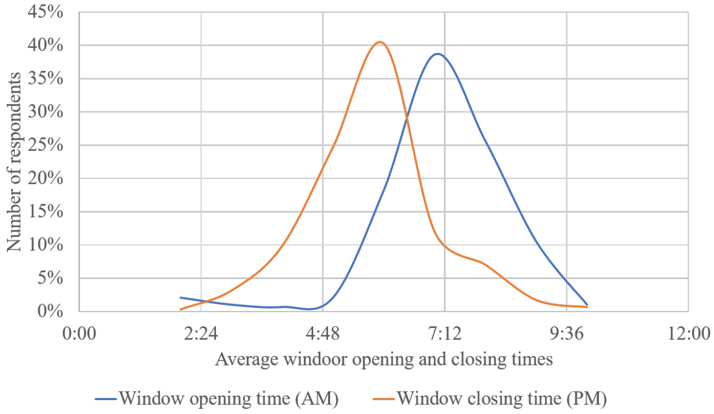


Figure 4.29: Average window opening schedules

The average lighting schedules of the respondents are shown in figure 4.30. As per the results, 47% of the respondents switch on the light at 5.00 AM and 65% switch off light at 7.00 AM. In the evening, 57% switch on light at 6.00 AM and 96% switch off light after 10.00 PM.

According to the literature, there is a strong correlation between floor area and the energy consumption (Yohanis et al., 2008). In designing the OB_{rate}, it was first hypothesised that, number of bedrooms (used as an indicator for floor area of the house) has an effect on the total energy consumption.

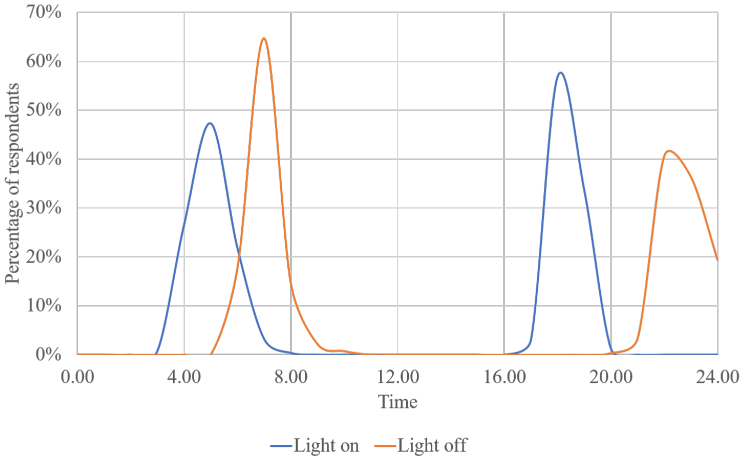


Figure 4.30: Average lighting schedules of the respondents

If such effect is found, it should be normalised so that OB rate only considers the effect of occupants' behaviours and decisions. When considering direct regression analysis between total electricity consumption and number of bedrooms, a positive correlation was found. Subsequently, a parametric analysis was conducted while taking total energy consumption as dependent variable and considering seven independent variables as follows.

- Number of occupants
- Number of occupants stay at home
- Shape of the house
- Number of floors in the house
- Number of bedrooms in the house
- Number of air conditioned spaces in the house
- Electricity consumption for equipments

When calculating the electricity consumed for equipments, the occupancy schedules of the respondents, number of bedrooms, and type and number of equipments were used. The result of the parametric analysis is indicated in table 4.19. As per the results of the parametric analysis, the number of occupants stay at home, building shape, and number of bedrooms were identified as not significant at 95% significance level.

Table 4.19: Parametric analysis of consumer survey: first run results

Model	Unstd Coeff (B)	Std Error	Std Coeff (B)	t	Sig.
(Constant)	9.648	17.824		0.541	0.589
No of Occupants	8.891	3.11	0.147	2.859	0.005
Stay at home	-1.7	3.698	-0.023	-0.46	0.646
Shape	3.998	3.036	0.065	1.317	0.189
Floors	28.872	6.495	0.256	4.446	0
Bedrooms	-0.144	2.934	-0.003	-0.049	0.961
A/C	41.671	6.895	0.317	6.044	0
Total equipment	0.119	0.045	0.134	2.671	0.008

Therefore, another parametric analysis was conducted removing not significant variables and the results indicate that the number of occupants, number of floors in the house, number of air conditioned spaces in the house and electricity consumed for equipments are significant variables. The results of the parametric analysis after omitting insignificant variables are presented in table 4.20.

Table 4.20: Parametric analysis of consumer survey: second run results

Model	Unstd Coeff (B)	Std Error	Std Coeff (B)	t	Sig.
(Constant)	16.563	15.914		1.041	0.299
No of Occupants	8.258	2.981	0.136	2.77	0.006
Floors	29.982	5.987	0.266	5.007	0
A/C	41.792	6.805	0.318	6.141	0
Total equipment	0.123	0.044	0.139	2.775	0.006

According to the parametric analysis results, number of bedrooms is not significant in total energy consumption and other factors such as number of occupants, number of floors, air conditioning and equipment usage affect more on the energy consumption. All the significant factors are based on the occupant conditions and decisions and therefore, the energy consumption data is used to develop OB_{rate} without normalising.

4.5.2 Development of OB_{rate}

Ranasinghe (2011) has conducted a survey on the requirements of prospective electricity consumers in Sri Lanka using 2541 households in Sri Lanka. As shown in table 4.21, 50% of the households are falling to the electricity consumption category of 31 - 91 kWh. Also, the average monthly electricity consumption is 73 kWh per month. According to PUCSL (2011), the total number of consumer accounts is 4572,084 and the total electricity sales in year 2011 was 3893 Gwh and therefore, the average electricity consumption per month was calculated as 71kWh. This value was used as the average for OB_{rate} calculation. Therefore as previously mentioned in methodology section, the OB_{rate} for Sri Lankan residential buildings can be calculated using equation 4.3

$$OB_{rate} = \frac{\text{Actual energy consumption}}{71} \times 100 \tag{4.3}$$

Table 4.21: Electricity consumption of Sri Lankan households

Consumption category	Sample stratification		Average	
	Number	%	Units	Cost (Rs.)
Less than 30	635	24.99	22.6	97.79
31-90	1273	50.10	63.16	347.61
91-180	508	19.99	120.16	1399.91
More than 180	125	4.92	227.04	4255.64
Total	2541	100	72.48	687.81

4.6 Sustainability assessment of energy sources

4.6.1 Analysis of sustainability assessment of rooftop solar PV in residential buildings

The distribution of the respondents among various fields including location number of people in the household are presented in table 4.22 and solar PV installation year and energy storage model are shown in table 4.23.

Table 4.22: Basic Information of the respondents

District of solar installed property		Number of people in household	
Ampara	2%	1	0%
Colombo	48%	2	2%
Galle	4%	3	23%
Gampaha	29%	4	37%
Hambantota	4%	5	29%
Kalutara	10%	6 or more	10%
kurunegala	2%		
Nuwara Eliya	2%		

Table 4.23: Basic information on PV installation

Solar PV installation year		Energy storage model	
2012	2%	Net metering	85%
2013	8%	Net accounting	10%
2014	12%	Battery pack	4%
2015	44%	Net metering with battery pack	2%
2016	25%		
2017	10%		

4.6.1.1 Consumption change after solar PV installation

The pre-post comparison of the electricity consumption of the respondents indicates a significant increase in consumption after the rooftop solar PV installation as shown in figure 4.31. Irrespective of the pre-installation energy consumption 69% of the respondents consume more than 400 units after installation.

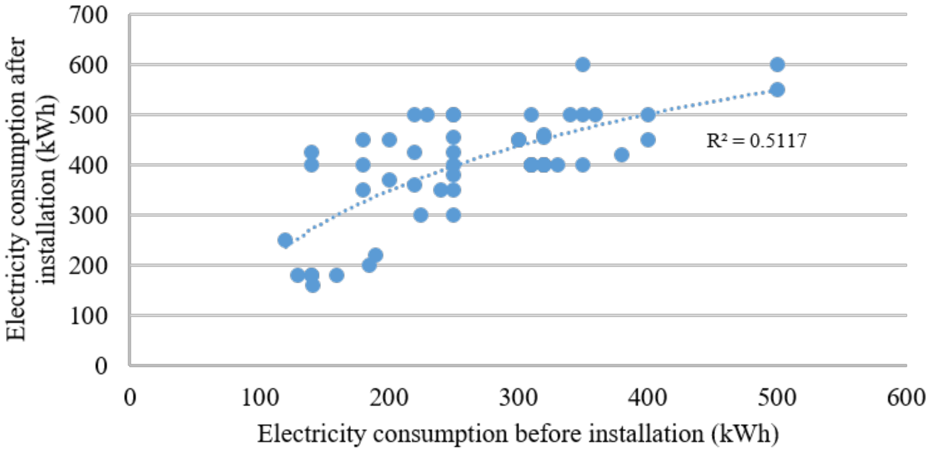


Figure 4.31: Electricity consumption before and after solar PV installation

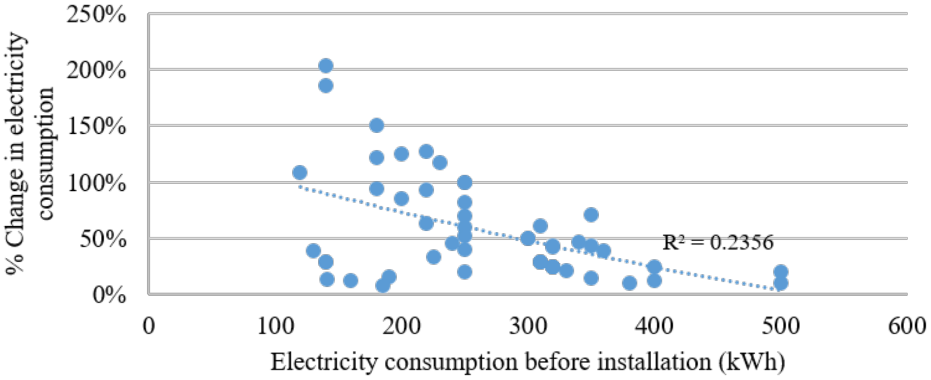


Figure 4.32: Percentage change in electricity consumption compared to the electricity consumption before installation

Figure 4.32 indicates the percentage change in electricity consumption compared to the electricity consumption before installation. The respondents with lower electricity consumption prior to installation (less than 250 kWh) do not show a distinctive pattern of consumption increase after installation where the change varies from 0% to more than 200%. The percentage change of the high consumers (prior installation) varies from 0% to 50% and demonstrate a negative correlation among electricity consumption before installation and percentage of consumption change.

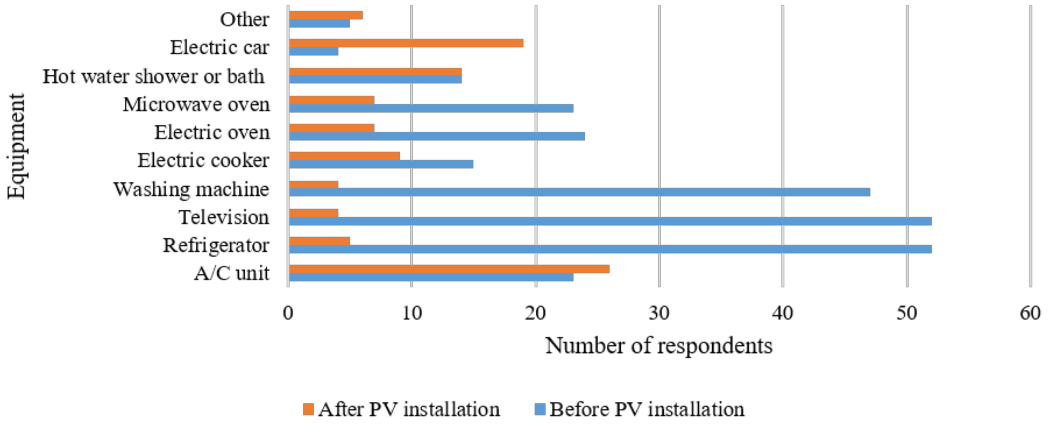


Figure 4.33: Equipment used before PV installation and purchased after installation

4.6.1.2 Reasons for consumption increase

As per the results discussed above the energy consumption significantly increase after the solar PV installation and the consumption is more than 400 kWh for the majority of the respondents. The higher energy consumption is mainly governed by high energy intensive equipment such as electric cars air-conditioned units or hot water showers or baths. Figure 4.33 illustrates the equipment used before solar PV installation and purchased after installation by the respondents. According to the questionnaire results the refrigerator television and washing machine are the basic electrical equipment used and 50% of the respondents had air-conditioning units and 10% had electric cars before solar installation. The higher electricity consumption before solar PV installation is mainly due to the air-conditioning units and electric cars. After the solar installation, 36% of the respondents have purchased an electric car and 50% have purchased air-conditioning unit which explains the reason for consumption increase after the solar PV installation.

Regardless the excess units produced by the solar PV system nearly 80% the respondents were aware of the increase in the post-installation energy consumption. Fifty-five percent of the respondents indicated that purchasing of new equipment have contributed to the increase. In addition to the equipment purchase, some other factors such as the addition of components to the house and increase in the number of members in the household may have affected the energy demand. However, 19% of the respondents who have comparatively lower consumption rise are not aware of the increase (figure 4.34).

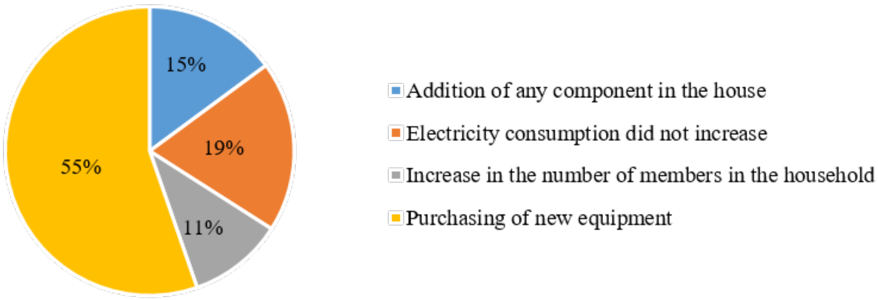


Figure 4.34: Reasons for increase in total electricity consumption

4.6.1.3 Solar PV sizing decision

The solar PV sizing decision is the primary element of the installation transaction process. In addition to the current energy consumption, the factors such as; future requirements, customer behaviour, and the net metering policy directly affect the solar PV size. The larger system size correlates with increased energy consumption generally reflects inefficient subsidy or barriers that disfavour energy conservation and efficiency (Fuerst, McAllister, Nanda, & Wyatt, 2016). The most rational decision by a customer would be to select a solar PV system size which maximizes the internal rate of return. However, 96% of the respondents have selected larger system sizes than required to meet the past energy consumption and to provide enough capacity to meet energy demand by future equipment usage. As shown in figure 4.35, 61% of the respondents are not utilizing the total electricity produced and supply to the grid as excess units.

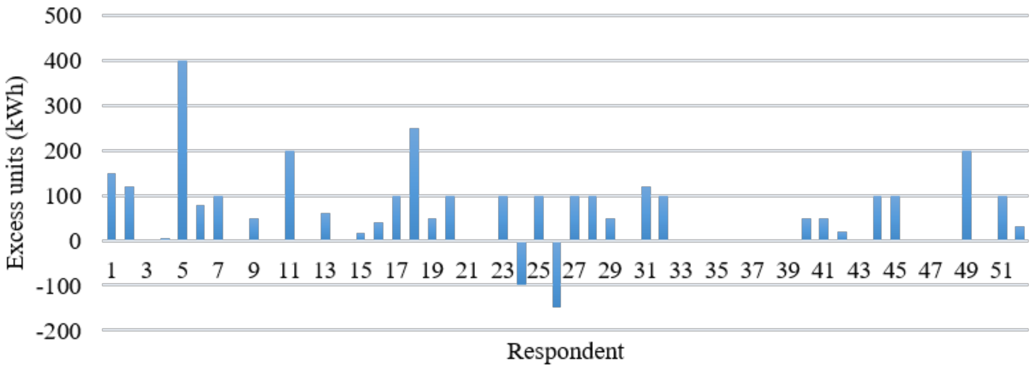


Figure 4.35: Excess units supplied to the main grid by the respondents

Table 4.24 presents the installation related decisions such as payback period, financing methods and method of deciding the system size by the respondent. Payback period is a significant criterion when selecting the system size and 69% of the respondents have got advice from solar company to decide solar PV system size.

Table 4.24: Installation related decisions

Payback period		Financing method		System size decision	
Less than 2 years	8%	Cash in hand	79%	Customer decided by matching own consumption	46%
2-5 years	54%	Solar power loan from bank	12%	Got advice from another person	4%
6-10 years	38%	Personal loan from a bank	13%	Got advice from solar company	69%

4.6.1.4 Rebound effect

The rebound effect or take back effect arises when the consumer takes back the energy saving of an energy efficiency investment due to higher consumption (Caird, Roy, & Herring, 2008). This concept cannot be directly attributed to the solar PV system which is not an energy consuming device. As per Fuerst et al. (2016), the rebound effect of solar PV directly attached with the income effect, where the consumers tend to increase the energy consumption with the decrease in marginal cost of electricity. In our case study, a clear sign of rebound effect is seen, since the difference between the post and prior installation energy consumption is significant as indicated in figure 4.31. As shown in figure 4.36, the principal motivations for solar PV installation are to reduce the electricity bill and to purchase additional energy consuming equipment without increasing the energy bill which explains this effect. Indirect rebound effect can occur if the saved money is re-spent on energy consuming devices (Chitnis, Sorrell, Druckman, Firth, & Jackson, 2013). Figure 4.37 illustrates the modes of utilization of the saved money from lower electricity bill by the respondents. Forty-four percent of the respondents save the money for the future uses. Although savings do not indicate direct energy consumption, this may have embodied energy through investment by the relevant financial institutions on energy incentive investments.

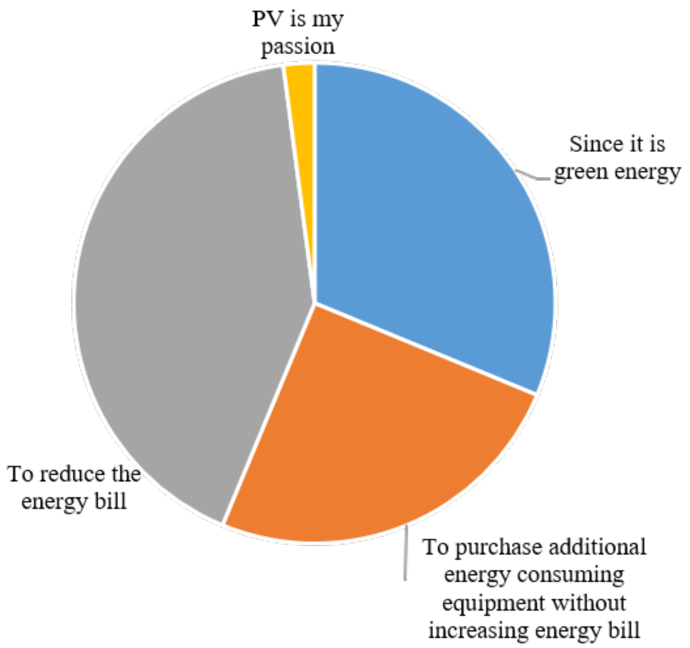


Figure 4.36: Motivation for installing rooftop solar PV system

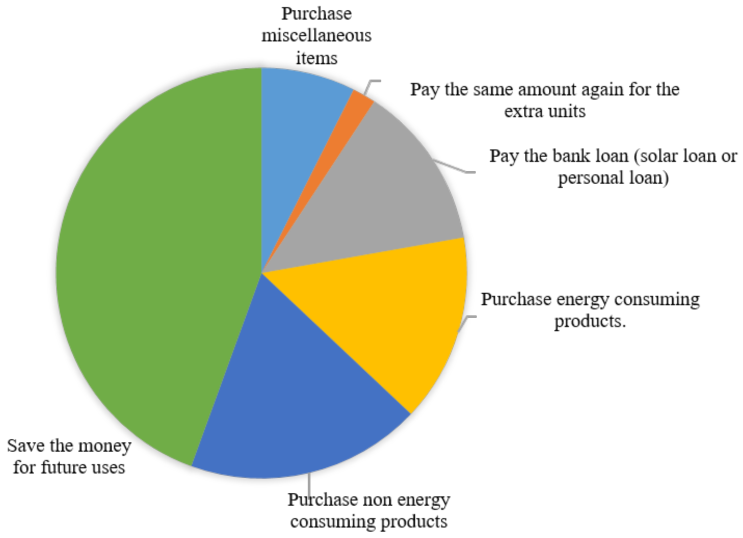


Figure 4.37: Utilization of the saved money from lower electricity bill

4.6.1.5 Social and environmental impact

The electricity consumption has a positive correlation with the economic development due to being at a higher tier of the energy ladder and higher economic capabilities that improve the ability to consume more energy intensive equipment. This is evident in case of Sri Lankan as indicated in figure 4.38. The demand for the electricity increases with the social and living status. Higher electricity cost appears as a main barrier for diffusion of the energy consuming equipment which improves the living conditions. The reduced marginal cost due to solar PV adoption would encourage such equipment purchases.

From the environmental perspective, this creates benefit for the environment as the electricity consumption after the increase is totally covered by renewable energy and more units will be contributed to the main grid. Figure 4.39 illustrates the electricity generation by various energy sources including hydropower, thermal, wind, new renewable energy and net metered projects of Sri Lanka. After 1996, the electricity generation from thermal sources has been increased rapidly. To cater the demand of more energy intensive equipment such as air-conditioning units which improve the living standards or the electric cars that minimize the greenhouse gas emissions, more fossil fuel would be burnt in the absence of solar PV system. Further, the purpose of encouraging electric cars would be effective only if renewable energy is used for charging purpose.

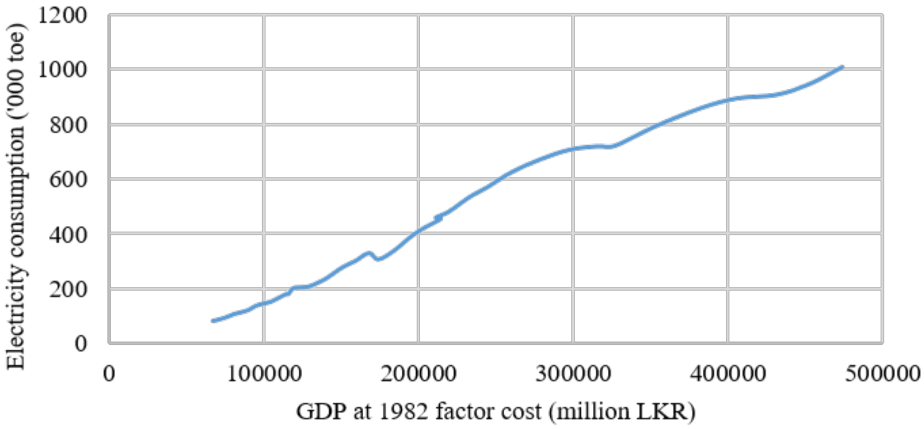


Figure 4.38: Electricity consumption compared to GDP (SLSEA, 2017)

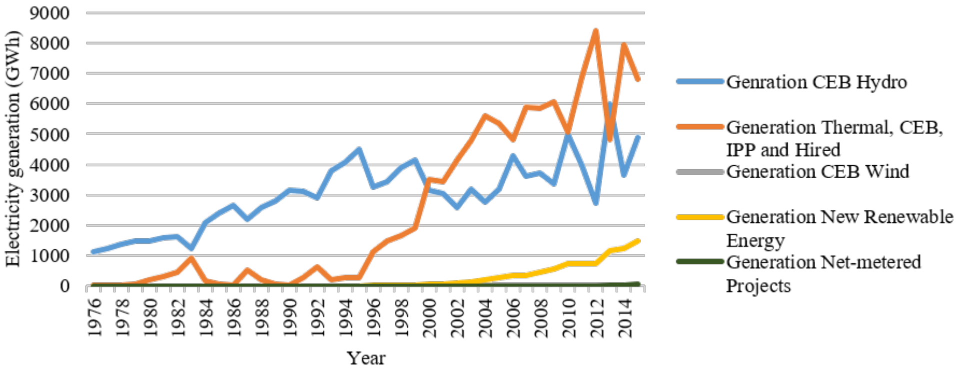


Figure 4.39: Electricity generation by various sources (SLSEA, 2017)

4.6.1.6 Impact on peak load and load balance

Despite the social and environmental benefits directly associated with solar PV electricity, a significant adverse effect may occur on the peak demand of daily electricity load. Figure 4.40 illustrates the daily load curve of Sri Lanka on the day of the annual peak from 2007 to 2014. The shape of the load curve does not show a significant change during this period. However, the curve is shifted upwards year by year which has increased the peak demand and the maximum peak recorded in the year 2014 is 2152 MW (Ceylon Electricity Board, 2015).

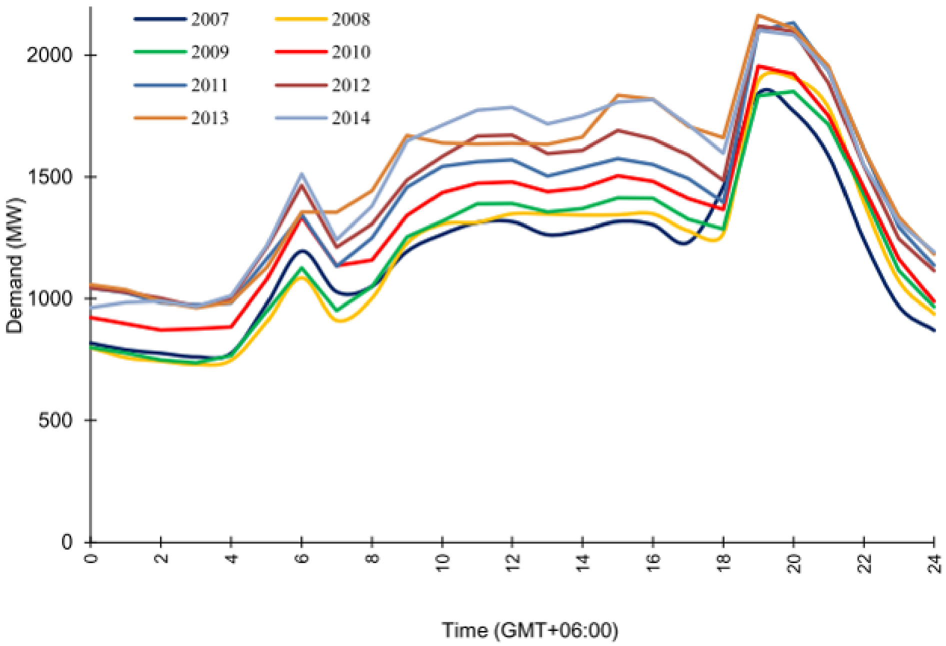


Figure 4.40: Change in daily load curves from 2007 to 2014 (Ceylon Electricity Board, 2015)

In Sri Lanka, the peak demand occurs from 19.00 to 22.00 hours daily where the electricity from solar PV system is generated only during daytime. The solar electricity can be used to reduce the daytime peak and the increased use of energy consuming equipment during night time may further increase the night time peak. However, the number of net metering customers compared to the total electricity consumers is still negligible and would not have a significant effect on the peak demand in short term. Nevertheless, in the long run, there can be a considerable effect on the peak load as the rapid diffusion of the solar PV system in the country due to its potential to reduce the electricity cost and the incentives including loan schemes. As indicated in figure 4.39, the electricity generation from net metered projects still does not have a significant contribution to the main grid. With the increase in the net metered connections, a grid upgrade would be required since it will affect the system resilience (Bletterie et al., 2011).

4.6.2 Development of Energy source rate ES_{rate}

From the questionnaire survey, it was identified that there is a clear indication of the rebound effect due to solar PV adoption in residential buildings and there are other social and technical aspects associated with it as discussed in the above. According to the sustainability index values proposed by Cartelle Barros et al. (2015) as shown in section 3.8, the sustainability index values for electricity generation mixes was calculated and the result is indicated in table 4.25. The percentage contribute of the energy sources to the electricity generation was obtained from the web site of Sustainable Energy Authority Sri Lanka for December 21, 2018 (SLSEA, 2018).

Table 4.25: Sustainability index values for energy mix

Source	% contribute to electricity generation	SI value	Index with percentage
Coal	15.85%	0.269	4.26
Oil	52.49%	0.31	16.27
Hydro	30.52%	0.61	18.62
Wind	0.47%	0.76	0.36

Using the index values with percentages in table4.25, the SI values for hypothetical electricity generation scenarios were developed assuming the household is using only the electricity from the main grid and Solar PV. The SI index values for those scenarios are illustrated in table 4.26. According to the results, the best scenario is the 100% electricity from Solar PV scenario which provides an SI index value of 69 and the worst scenario is 100% electricity from coal that gives SI index of 27. The electricity from grid gives a SI index value of 39.51.

Table 4.26: Sustainability index values for energy generation scenarios

Scenario	% Electricity from grid	% Electricity from Solar PV	Total index
Scenario 1	100%	0%	39.51
Scenario 2	75%	25%	46.88
Scenario 3	50%	50%	54.56
Scenario 4	25%	75%	61.23
Scenario 5	0%	100%	69

4.7 Development of energy score

The development of energy rating system involves the deriving energy score and preparing a comparability scale. Firstly, the energy score was developed using the three sub-rates developed in the previous sections. When developing the final energy score, all the sub-rates should be brought to a common scale which is done by normalising. Therefore, all the three sub rates were normalised as discussed below.

4.7.1 Normalising the BC_{rate}

For normalising BC_{rate} it is required to calculate the minimum and maximum rates first as discussed in methodology section. As given in equation 4.4 the $BC_{rate(min)}$ was calculated by taking the fraction of $BC_{rate(Optimum)}$ and $BC_{rate(worst)}$ and multiplied by 100. The value for $BC_{rate(worst)}$ (62.892) was obtained from the full AC scenario (all three bedrooms and living rooms are air conditioned) which was calculated in table 4.17. Similarly the $BC_{rate(max)}$ was calculated using the results of optimum rates which gives a rating of 100 which is the maximum value as shown in equation 4.5. Finally, the Normalized BC_{rate} was calculated using equation 4.6 which enables all the future values will fall in 0 to 100 scale.

$$\begin{aligned}
BC_{rate(min)} &= \left(\frac{BC_{rate(Optimum)}}{BC_{rate(Worst)}}\right) \times 100 \qquad (4.4)\\
&= \left(\frac{3.85}{62.892}\right) \times 100\\
&= 6.1216
\end{aligned}$$

$$\begin{aligned}
BC_{rate(max)} &= \left(\frac{BC_{rate(Optimum)}}{BC_{rate(Optimum)}}\right) \times 100 \qquad (4.5)\\
&= \left(\frac{3.85}{3.85}\right) \times 100\\
&= 100
\end{aligned}$$

$$\begin{aligned}
\text{Normalized } BC_{rate} &= \left(\frac{BC_{rate(Actual)} - BC_{rate(Minimum)}}{BC_{rate(Maximum)} - BC_{rate(Minimum)}}\right) \times 100 \qquad (4.6)\\
&= \left(\frac{BC_{rate(Actual)} - 6.1216}{100 - 6.1216}\right) \times 100\\
&= \left(\frac{BC_{rate(Actual)} - 6.1216}{93.8784}\right) \times 100
\end{aligned}$$

4.7.2 Normalising the OB_{rate}

Similar to the normalised BC_{rate}, the minimum and maximum OB_{rate}m were calculated for normalised OB_{rate}. However, unlike in the previous case, the upper and lower margins had to be separately calculated. To get the lower margin of the scale, the minimum energy consumption value has to be selected and according to Ranasinghe (2011), the minimum requirement for a decent life standard is 48kWh and therefore the lower margin for OB_{rate} was calculated using that value as shown in equation 4.7.

$$\begin{aligned} OB_{rate(min)} &= \frac{\text{Minimum energy consumption}}{71} \times 100 \qquad (4.7) \\ &= \frac{48}{71} \times 100 \\ &= 68.57 \end{aligned}$$

The upper margin of the scale (equation 4.8 was taken by the maximum energy consumption which was calculated using the total energy consumption by upper 180 units category (596 GWh) and the total number of households using more than 180 units per month PUCSL (2011).

$$\begin{aligned} \text{Maximum energy consumption} &= \frac{596 \text{ GWh}}{162462} \qquad (4.8) \\ &= 306 \text{ kWh} \end{aligned}$$

$$\begin{aligned} OB_{rate(max)} &= \frac{\text{Maximum energy consumption}}{71} \times 100 \qquad (4.9) \\ &= \frac{306}{71} \times 100 \\ &= 431 \end{aligned}$$

After determining the lower and upper margins of the OB_{rate} it is required to convert it to a normalised scale (0 to 100) where, for lower consumptions higher marks should be allocated and higher consumptions lower marks should be given. To meet this requirement, the equation 4.10 was used.

$$\begin{aligned} \text{Normalised } OB_{rate} &= \left[1 - \left(\frac{\text{Actual } OB_{rate} - OB_{rate(min)}}{OB_{rate(max)} - OB_{rate(min)}}\right)\right] \times 100 \qquad (4.10) \\ &= \left[1 - \left(\frac{\text{Actual } OB_{rate} - 68.57}{431 - 68.57}\right)\right] \times 100 \\ &= \left[1 - \left(\frac{\text{Actual } OB_{rate} - 68.57}{363.39}\right)\right] \times 100 \end{aligned}$$

4.7.3 Normalising the ES_{rate}

To develop the normalise ES_{rate}, a similar approach used for BC_{rate} was used. Here for the upper margin of the scale (best value), the index value of 100% solar PV (SI=69) was used and for the lower margin of the scale (worst value), the index value of 100% from coal (SI=27) was used. The calculation used for normalising the ES_{rate} is shown in equation 4.11.

$$\begin{aligned}\text{Normalized } ES_{rate} &= \left(\frac{\text{Actual index value} - \text{SI 100\% coal}}{\text{SI 100\% solar PV} - \text{SI 100\% coal}}\right) \times 100 \quad (4.11)\\ &= \left(\frac{\text{Actual index value} - 27}{69 - 27}\right) \times 100\\ &= \left(\frac{\text{Actual index value} - 27}{42}\right) \times 100\end{aligned}$$

4.7.4 Developing the energy score

Eighty percent of the respondents were from engineering field (Civil and Electrical), 12% were architects, 6% were quantity surveyors and 2% were from facilities management field. The table 4.27 indicates the percentage of scores received for the three factors; building characteristics, occupancy behaviour and energy score.

Using the questionnaire results, the relative importance of each factor was calculated by taking the weighted average. Then the weightage was calculated using equation 4.12 where; RI_i is the relative importance of factor i.

$$Weightage = \frac{RI_i}{\sum_{i=1}^{3} RI_i} \quad (4.12)$$

Table 4.27: Percentage of scores received for the three factors

Score	Building characteristics	Occupancy behaviour	Energy source
1	0%	4%	3%
2	2%	6%	6%
3	10%	14%	14%
4	33%	38%	42%
5	55%	38%	34%

Table 4.28: Percentage of scores received for the three factors

	BC_{rate}	OB_{rate}	ES_{rate}
Relative Importance	4.42	4.01	3.99
Weightage	0.36	0.32	0.32

Table 4.29: Values used for hypothetical scenarios

Modeled electricity consumption (kWh)	Actual electricity consumption (kWh)	Energy source
3.85 (Best)	48 (Best)	100% grid
10	73 (Average)	75% grid 25% solar
30	90	50% grid 50% solar
50	120	25% grid 75% solar
62.892 (Worst)	180	100% solar
	306 (Worst)	

The calculated weigtages are available in table 4.28. According to the results, BC_{rate} which reflect the building characteristics has the highest weightage and other two are considered as equally important.

4.8 Developing the energy rating scale

The scale of this energy rating system is 0 to 100 scale where, zero is the worst case and 100 is the best or the optimum case. The final score for the scale can be calculated using the equation 4.13.

$$\text{Energy rating score} = 0.36BC_{rate} + 0.32OB_{rate} + 0.32ES_{rate} \tag{4.13}$$

In order to develop the scale, several hypothetical scenarios were built to check the margins for the scale. The modeled energy consumption, actual energy consumption values and the energy sources used for hypothetical scenarios are given in table 4.29. Altogether 150 scenarios were built and the final score for each scenarios is presented in table C.1 in annex C.

According to the scenario results, a hysterogram was drawn to identify the distribution of the cases. The figure 4.41 shows the distribution of the energy score for the given 150 scenarios. The mean of the 150 dataset is 52 and the standard

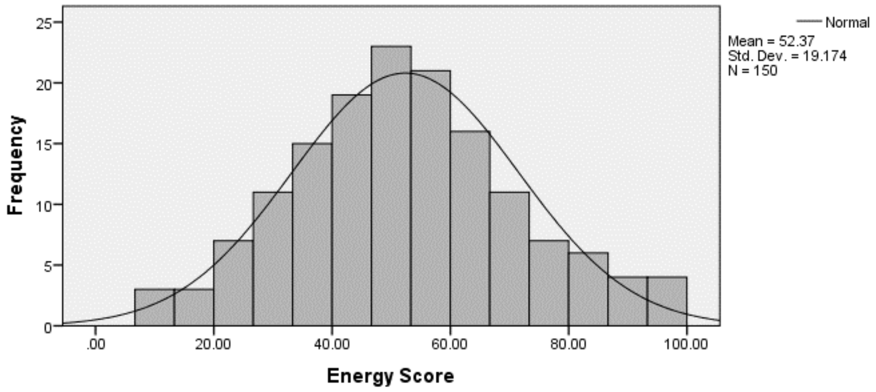


Figure 4.41: Distribution of the energy score

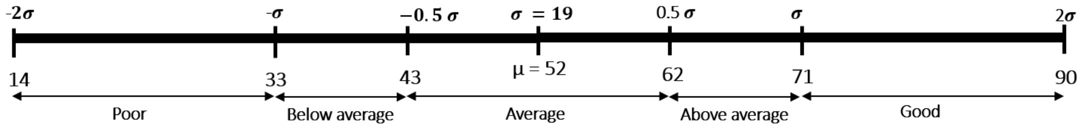


Figure 4.42: Energy rating scale with standard deviations

deviation is 19. The scale was developed so that the labels are defined based on the standard deviation. From -2σ to $-\sigma$ the label is Poor energy performance, $-\sigma$ to -0.5σ Below average energy performance -0.5σ to 0.52σ Average energy performance, 0.5σ to σ Above average energy performance and σ to 2σ Good energy performance. Figure 4.42 shows the scale with energy score categories according to standard deviation. Based on these figures the score categories relevant to labels were identified. The score category 0-13 is defined as not energy efficient. Score category 14-32 is defined as the poor energy performance, 33-42 as below average energy performance, 43-61 as average energy performance, 62-70 as above average energy performance and 71-89 as good energy performance and 90-100 as best energy performance. The completed scale is illustrated in figure 4.43

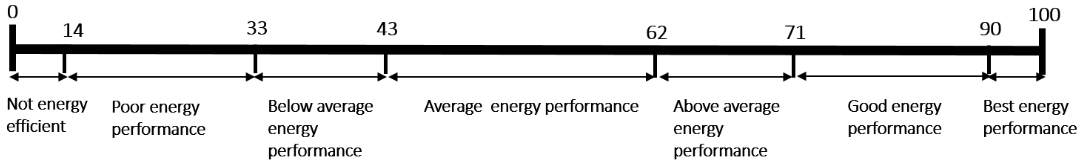


Figure 4.43: Energy rating scale

4.9 Summary

Using the parametric analysis, an optimum model was developed which reduce the discomfort hours to 148 hours (without additional air velocity) and achieve 1153 kWh lighting electricity per year. This was used as the reference value for developing the BC_{rate}. Further, the questionnaire survey results reviewed that there is no significant correlation between the number of bedrooms and actual energy consumption and it rather governed by the equipment usage which is an significant occupancy factor. Therefore, for developing OB_{rate}, the average of energy consumption in Sri Lankan household was used. For ES_{rate}, various scenarios were identified for application of renewable energy. The best scenario has 100% solar PV use which have a SI value of 69 and the worst scenarios is with 100% electricity from main grid and the related SI value is 39.51. By combining the three sub ratings, a final score was developed (Energy rating score $= 0.36BC_{rate} + 0.32OB_{rate} + 0.32ES_{rate}$). A scale was developed to indicate the energy performance of the houses. The score category 0-13 is defined as not energy efficient. Score category 14-32 is defined as the poor energy performance, 33-42 as below average energy performance, 43-61 as average energy performance, 62-70 as above average energy performance and 71-89 as good energy performance and 90-100 as best energy performance. Next chapter would discuss the application of the energy rating system to two actual sample buildings and the sensitivity analysis.

CHAPTER 5

APPLICATION OF THE ENERGY RATING SYSTEM

5.1 General

This chapter explains the application of the developed energy rating system in an actual scenario. The actual building properties and electricity bill information was used for the model and applying to the rating scale.

5.2 Applying the rating system to actual sample houses

To explain the use of the energy rating system proposed in this thesis, the method was tested by applying to two actual three bedroom, two story houses. The calculated scores and the results are presented below.

5.2.1 Sample house 1

The first sample house is an actual three bedroom, two story house (figure 5.1. This sample house size is large and total building area is 210.07 m^2 and the floor area of the smallest bedroom is 12.44 m^2 and largest bedroom is 37 m^2.

5.2.1.1 Calculating the BC_{rate}

In order to calculate the BC rate, first the house model was prepared with the schedules and conditions set for the optimum model. Then, the simulation was run for 22^nd May and obtained the hours which fall in to the operative temperature category as shown in table 5.1. Then, for the hours that do not comply the comfort requirements, the model was run with air conditioning which will operate only when the operative temperature exceed $32.4C^0$. The number of fans were allocated based on the minimum area covered by one fan and the shape of the rooms and the electricity required for the fans were calculated.

Figure 5.1: Sample house 1

This was added to the electricity for air conditioning and the total energy requirement to achieve thermal comfort was obtained as shown in table 5.2. The thermal comfort energy requirement is 44.11 kWh and the lighting electricity requirement is 17.99 kWh. Therefore the total energy requirement for the sample house is 62.1 kWh.

The BC_{rate} for the sample was calculated using equation 5.1 and the result was 6.2.

$$\begin{aligned} BC_{rate(Actual)} &= \left(\frac{BC_{rate(Optimum)}}{BC_{rate(Actual)}}\right) \times 100 \qquad (5.1) \\ &= \left(\frac{3.85}{62.1}\right) \times 100 \\ &= 6.2 \end{aligned}$$

Table 5.1: Number of hours in operative temperature categories in sample house

Zone	Operative temperature category		
	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Bedroom Ground floor	0	8	4
Living Ground floor	3.5	5	1
Pantry Ground floor	1.5	6.5	2
Dining Ground floor	3	8	2
TV room Ground floor	3.5	5	2
Bedroom 1 First floor	0	4	4
Living First floor	2	5.5	2
TV room First floor	0	5.5	4
Bedroom 2 First floor	3.5	5	1

Table 5.2: Total energy consumption in sample house 1

Zone	Fan speed Medium (hrs)	Fan speed high (hrs)	No of fans	Total power for fans (kWh)	AC (kWh)	total (kWh)
Bedroom Ground floor	8	4	2	1.032	1.64	2.672
Living Ground floor	8.5	1	2	0.609	2.95	3.559
Pantry Ground floor	8	2	1	0.366	3	3.366
Dining Ground floor	11	2	2	0.894	0.19	1.084
TV room Ground floor	8.5	2	1	0.3795	1.12	1.4995
Bedroom 1 First floor	4	4	1	0.408	4.41	4.818
Living First floor	7.5	2	2	0.705	6.09	6.795
TV room First floor	5.5	4	2	0.897	8.37	9.267
Bedroom 2 First floor	8.5	1	3	0.9135	10.14	11.0535
					Total	44.114

The normalised BC_{rate} for the sample was calculated using equation 5.8 and the result was 0.08. Main reason for having such a poor rate for the building characteristics is the large house size and higher thermal discomfort inside the house.

$$\begin{aligned}\text{Normalized } BC_{rate} &= \left(\frac{BC_{rate(Actual)} - 6.1216}{93.8784}\right) \times 100 \qquad (5.2)\\ &= \left(\frac{6.2 - 6.1216}{93.8784}\right) \times 100\\ &= 0.08\end{aligned}$$

5.2.1.2 Calculating the OB_{rate}

The actual average monthly electricity consumption of the sample house was 266 kWh. Using this figure, the actual OB_{rate} can be calculated using equation 5.9 and the normalised OB_{rate} can be calculated using equation 5.10. The result for the normalised OB_{rate} is 15.5.

$$\begin{aligned}OB_{rate(Actual)} &= \frac{\text{Actual electricity consumption}}{71} \times 100 \qquad (5.3)\\ &= \frac{266}{71} \times 100\\ &= 374.4\end{aligned}$$

$$\begin{aligned}\text{Normalised } OB_{rate} &= \left[1 - \left(\frac{\text{Actual } OB_{rate} - 65.75}{353.4}\right)\right] \times 100 \qquad (5.4)\\ &= \left[1 - \left(\frac{374.4 - 67.61}{363.39}\right)\right] \times 100\\ &= 12.6\end{aligned}$$

5.2.1.3 Calculating the ES_{rate}

The sample house is only electrified through the main grid and therefore,the normalised ES_{rate} can be calculated as given in equation 5.11 and the result is 30.

$$\begin{aligned}\text{Normalized } ES_{rate} &= \left(\frac{\text{Actual index value} - 27}{42}\right) \times 100 \qquad (5.5)\\ &= \left(\frac{39.51 - 27}{42}\right) \times 100\\ &= 30\end{aligned}$$

5.2.1.4 Calculating the total score and applying to the scale

The final score for the scale can be calculated using the equation 5.12.

$$\begin{aligned}\text{Energy rating score} &= 0.36BC_{rate} + 0.32OB_{rate} + 0.32ES_{rate} \qquad (5.6)\\ &= 0.36 \times 0.08 + 0.32 \times 12.6 + 0.32 \times 30\\ &= 14\end{aligned}$$

In the scale, this house will be in "Poor energy performance" rage as the score is 14. However, this situation can be changed if the house is modeled by considering the micro climate as well. Therefore, when properly applying this methodology, the house should be modeled with nearby shades (trees and buildings) as well. This will help to get the accurate figures for the energy rating as when designing a house, the macroclimatic features are heavily considered.

5.2.2 Sample house 2

The second sample house is an actual three bedroom, two story house (figure 5.2. The total floor area of the house is $93.75m^2$. The floor areas of living, dining, kitchen and three bedrooms are 19, 17, 11, 10, 15 and $19m^2$ respectively.

5.2.2.1 Calculating the BC_{rate}

Similar approach used in sample house 1 was carried out in modeling and simulating the sample house 2. The operative temperature categories of the second sample house are shown in table 5.3. Then, for the hours that do not comply the comfort requirements, the model was run with air conditioning which will operate only when the operative temperature exceed $32.4C^0$.

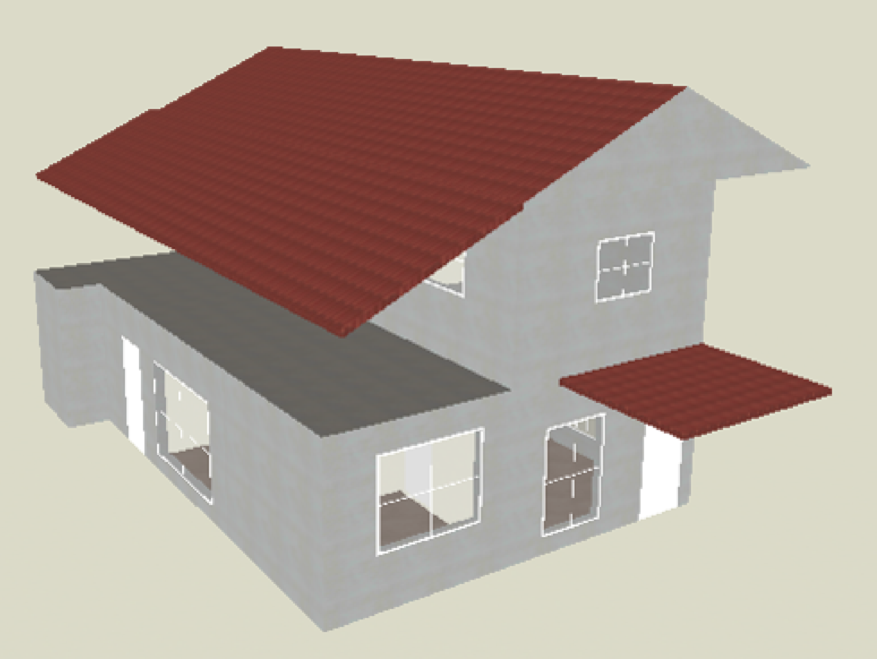


Figure 5.2: Sample house 2

The number of fans were allocated based on the minimum area covered by one fan and the shape of the rooms and the electricity required for the fans were calculated. This was added to the electricity for air conditioning and the total energy requirement to achieve thermal comfort was obtained as shown in table **??**. The thermal comfort energy requirement is 19.187 kWh and the lighting electricity requirement is 8.71 kWh. Therefore the total energy requirement for the sample house is 27.9 kWh.

The BC_{rate} for the sample was calculated using equation 5.1 and the result was 9.18.

$$\begin{aligned} BC_{rate(Actual)} &= \left(\frac{BC_{rate(Optimum)}}{BC_{rate(Actual)}}\right) \times 100 \qquad (5.7) \\ &= \left(\frac{3.85}{41.9}\right) \times 100 \\ &= 9.18 \end{aligned}$$

Table 5.3: Number of hours in operative temperature categories in sample house 2

Zone	Operative temperature category		
	30.00≤ 31.00>	31.00≤ 32.00>	32≤ 32.4>
Living	12	7	3
Dining	6	9.5	2.5
Kitchen	11.5	6	3.5
Bedroom 1	20.5	3	0
Bedroom 2	9.5	8.5	6
Bedroom 3	0	5	1

Table 5.4: Total energy consumption in sample house 2

Zone	Fan speed Medium (hrs)	Fan speed high (hrs)	No of fans	Total power for fans (kWh)	AC (kWh)	total (kWh)
Living	19	3	2	1.467	6.35	7.826
Dining	15.5	2.5	1	0.606	7.29	8.76
Kitchen	17.5	3.5	2	1.47	0	0.486
Bedroom 1	23.5	0	2	1.269	7.41	8.016
Bedroom 2	18	0	1	0.486	0	1.269
Bedroom 3	5	2	2	0.57	6.31	6.88
					Total	33.237

The normalised BC_{rate} for the sample was calculated using equation 5.8 and the result was 3.26. Main reason for having such a poor rate for the building characteristics is the large house size and higher thermal discomfort inside the house.

$$\begin{aligned}\text{Normalized } BC_{rate} &= \left(\frac{BC_{rate(Actual)} - 6.1216}{93.8784}\right) \times 100 \qquad (5.8)\\ &= \left(\frac{9.17 - 6.1216}{93.8784}\right) \times 100\\ &= 3.26\end{aligned}$$

5.2.2.2 Calculating the OB_{rate}

The actual average monthly electricity consumption of the sample house was 120 kWh. Using this figure, the actual OB_{rate} can be calculated using equation 5.9 and the normalised OB_{rate} can be calculated using equation 5.10. The result for the normalised OB_{rate} is 169.

$$\begin{aligned}OB_{rate(Actual)} &= \frac{\text{Actual electricity consumption}}{71} \times 100 \qquad (5.9)\\ &= \frac{120}{71} \times 100\\ &= 169\end{aligned}$$

$$\begin{aligned}\text{Normalised } OB_{rate} &= \left[1 - \left(\frac{\text{Actual } OB_{rate} - 65.75}{353.4}\right)\right] \times 100 \qquad (5.10)\\ &= \left[1 - \left(\frac{169 - 67.61}{363.39}\right)\right] \times 100\\ &= 70.78\end{aligned}$$

5.2.2.3 Calculating the ES_{rate}

The sample house is only electrified through the main grid and therefore,the normalised ES_{rate} can be calculated as given in equation 5.11 and the result is 30.

$$\begin{aligned}\text{Normalized } ES_{rate} &= \left(\frac{\text{Actual index value} - 39.51}{29.49}\right) \times 100 \qquad (5.11)\\ &= \left(\frac{39.51 - 27}{42}\right) \times 100\\ &= 30\end{aligned}$$

5.2.2.4 Calculating the total score and applying to the scale

The final score for the scale can be calculated using the equation 5.12.

$$\begin{aligned}\text{Energy rating score} &= 0.36BC_{rate} + 0.32OB_{rate} + 0.32ES_{rate} \qquad (5.12)\\ &= 0.36 \times 3.26 + 0.32 \times 70.76 + 0.32 \times 30\\ &= 34\end{aligned}$$

In the scale, this house will be in “Below average energy efficiency”. Although the building energy consumption is higher due to poor building design, the consumer behaviour due to lesser actual electricity consumption has resulted a better rating than the sample 1.

5.3 Sensitivity Analysis

The variables in the sample house 1 was modified to conduct the sensitivity analysis. The results of the sensitivity analysis is shown in table 5.5.

According to the sensitivity analysis, it is clear that by optimising only one variable, it is not possible to archive beyond below average energy efficiency level. By achieving the all the improvements, this house can get good energy performance label.

Table 5.5: Sensitivity analysis

Scenario	Thermal	Usage	Energy scenario	Score	Label
Original	44.11	266	100% Grid	14	Poor
Thermal improvement	0	-	-	19	Poor
Usage improvement - Level 1	-	115	-	33	Below average
Usage improvement - Level 2	-	48	-	41	Below average
Thermal + Usage improvement	0	48	-	47	Average
Energy source improvement	-	-	100% Solar	36	Below average
Thermal + Energy source	0	-	100% Solar	41	Below average
Usage + Energy source - Level 1	-	210	100% Solar	43	Average
Usage + Energy source - Level 2	-	62	100% Solar	62	Above average
Thermal + Usage + Energy	0	48	100% Solar	70	Good

CHAPTER 6

DISCUSSION

When implementing any new system, a graphical representation of the system enables easy understanding and broad acceptance of the proposed model. Therefore a graphical representation of the model was prepared considering the importance of having overall information for policy making purposes as illustrated in figure 6.1. As illustrated in the chart, the main information required to consider the rating for a particular building are the building information including the building plan, building materials and locations; actual average monthly electricity consumption of the house and the electricity generation scenario with the percentage from each source. After getting information, the house model will be prepared with Design Builder software considering the microclimate effects and then the total electricity consumption for lighting will be obtained from the simulation results and the electricity consumed for thermal comfort will be calculated based on the hours falling in to various operative temperature categories. The SI value for the energy mix is calculated based on the energy scenario of the house and the OB_{rate}, BC_{rate} and ES_{rate} are calculated using the given equations. All these rates are normalised and aggregated to get the energy score and the label is obtained from the scale developed for energy rating.

The proposed sustainable energy rating system would mainly focus on the promotion of the use of sustainable energy in the building sector. This considers all the pilers of the sustainable energy which covers the energy efficiency of the building, energy efficient consumer behaviour and the renewable energy sources. The existing energy rating systems are mainly focusing on the energy efficiency and renewable energy where the proper aggregation of the all sustainable energy aspects have been neglected. Therefore, the model proposed by this thesis can be used by the policy makers and the government in achieving the SDCs and NDCs.

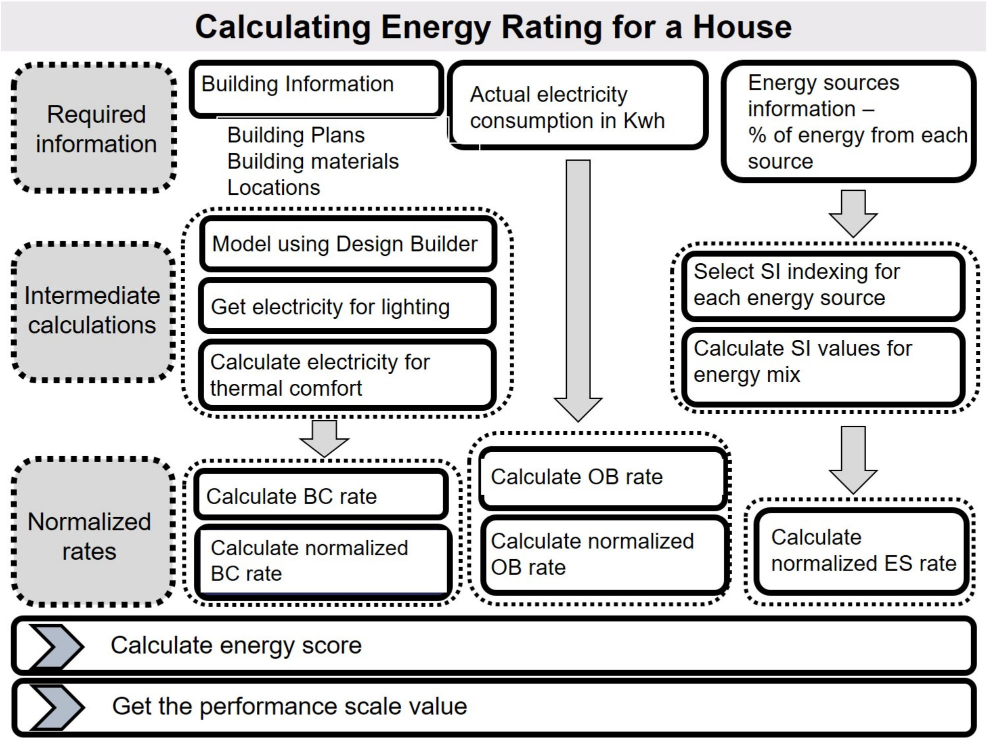


Figure 6.1: Graphical representation of the final model

The weights of the energy score equation, actually should be based on the policy initiatives. When implementing the energy rating system in wide scale, an expert interview should be conducted at policy level including all the parties related to implement and design the policy. The experts should include all the stakeholder including the policy makers, industry experts and the academia. Based on the importance of the relevant criteria for the particular policy the weightage will be allocated. For example, if the main aim of introducing the energy rating is to improve the market value of the building, then more score should be given to the BC_{rate}, and if it is to encourage energy efficiency behaviour of the occupants, then OB_{rate} should be prioritised and if the policy is to promote renewable energy, the more weightage should be allocated to ES_{rate}. The main advantage of this model is that it can be easily adapted to any policy requirement, any building type and any country by changing the reference values and weights.

As limitations, this model will only consider the global sustainability aspects of the energy source and the on site aspects are not considered. For example, the efficiency of the individual Solar panel in the house is not considered and considered it as out of scope. In the future it is possible to include the individual system efficiencies to the sustainability index of the energy source when localising the values to the local requirements.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Energy represents a considerably higher percentage of running cost of a building and also affects the optical and thermal comfort of the occupants. The energy rating systems is seen as an efficient way to address the energy issue and it is a key policy instrument that will assist government to reduce the energy consumption. SLSEA has now developed a Code of practice for energy efficient buildings in Sri Lanka and has raised the concern that the buildings complying with the energy code should be given an energy rating and need to develop a scheme for that purpose. The main conclusions of the thesis are as follows.

- The existing rating systems fall into either calculated rating or measured rating. Using only one rating method may not provide the true picture on the energy consumption scenario of the building and therefore, several attempts are there to make a hybrid method. The only available hybrid system is MOHOURD system in China although the integration is not yet successful. Therefore, a new system should be made with both assets and measured rating, which can be altered easily based on policy changes, country and climate.

- When evaluating the building energy performance, thermal comfort receives a special emphasise. For tropical climates, specially for naturally ventilated buildings, ASHRAE 55 adaptive comfort standards provide better thermal comfort perceptions and can be used for thermal comfort calculations for naturally ventilated buildings.

- In addition to thermal comfort, the lighting energy also depends on the building characteristics. The previous works are much forecasted on heating and cooling demand, rather focusing on naturally ventilated residential buildings. Also, the effect of zones on thermal comfort and lighting are highly neglected in the past studies. Therefore, the methodology should focus on the effect of zones and zone locations of the naturally ventilated buildings.

- In addition to the building properties, the consumer behaviour affects significantly to the energy performance of the building. The door and window opening behaviours and equipment usage, maintainable and purchase decisions are highly affected by various occupant characteristics and need to be considered in developing the energy rating.
- The sustainability assessment of energy sources are mainly in three main categories as social, economic and environmental and when using an index value for sustainabile assessment of energy sources, all these aspects should be considered.
- Considering the inadequacies of the existing systems, this research developed a new energy rating methodology which is based on sustainable energy concept. In this concept, both energy efficiency and the renewable energy sources are considered and in energy efficiency, the energy consumed due to building characteristics and due to occupancy behaviour are considered.
- Three ratings were prepared to cover each aspect named; BC_{rate} for energy consumption due to building characteristics, OB_{rate} for energy consumption due to occupancy behaviour and ES_{rate} for the energy source.
- To develop BC_{rate} an optimum building was designed by analysing and conducting parametric study of 4569 models varying, orientation, window to wall ratios, zone locations, zone sizes, building shape etc. A questionnaire survey was conducted to obtain the reference values for the occupancy, lighting and other schedules. To develop the ES_{rate}, the sustainability index proposed by Cartelle Barros et al. (2015) was used.
- All these rates were then normalised to 0-100 scale and combined through weightage factors obtained through a questionnaire results which was based on the perception of the construction industry.
- Using the parametric analysis, an optimum model was developed which reduce the discomfort hours to 148 hours (without additional air velocity) and achieve 1153 kWh lighting electricity per year. This was used as the reference value for developing the BC_{rate}.

- The questionnaire survey results reviewed that there is no significant correlation between the number of bedrooms and actual energy consumption and it rather governed by the equipment usage which is an significant occupancy factor. Therefore, for developing OB_{rate}, the average of energy consumption in Sri Lankan household was used.

- For ES_{rate}, various scenarios were identified for application of renewable energy. The best scenario has 100% solar PV use which have a SI value of 69 and the worst scenarios is with 100% electricity from main grid and the related SI value is 39.51.

- By combining the three sub ratings, a final score was developed as follows Energy rating score $= 0.36BC_{rate} + 0.32OB_{rate} + 0.32ES_{rate}$.

- A scale was developed to indicate the energy performance of the houses. The score category 0-13 is defined as not energy efficient. Score category 14-32 is defined as the poor energy performance, 33-42 as below average energy performance, 43-61 as average energy performance, 62-70 as above average energy performance and 71-89 as good energy performance and 90-100 as best energy performance.

7.1 Recommendations and future work

The reference values used in this thesis will be only applicable to Katunayaka climate zone and for two story, three bedroom houses which operate with natural ventilation with fans. The methodology proposed in the thesis should be used to develop the reference values to other climate zones, and other house types and building types. When preparing the actual model, the effect of micro climate should be considered and the adjacent buildings and trees also should be modeled with the actual building to get the effect of shadings. Modeling the building considering the macroclimatic effect is quite a difficult task and therefore, as a future work it is possible to model the houses with various microclimate situations and develop an equation for use in any building. This model also can be altered and used for other types of buildings such as industries and commercial buildings. In industrial buildings, the rating system has to be normalised for the type of industry and number of machinery etc. and in commercial buildings, the rating system need to normalised for the commercial activity type and the floor area.

The weights of the energy score equation, actually should be based on the policy initiatives. When implementing the energy rating system in wide scale, an expert interview should be conducted at policy level including all the parties related to implement and design the policy. For example, if the main aim of introducing the energy rating is to improve the market value of the building, then more score should be given to the BC_{rate}, and if it is to encourage energy efficiency behaviour of the occupants, then OB_{rate} should be prioritised and if the policy is to promote renewable energy, the more weightage should be allocated to ES_{rate}.

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APPENDIX A

Outdoor temperature of weather file

Table A.1 indicates the monthly average temperatures indicated in the input weather file. This was used to determine the hottest month in the year in acceptable limits of operating temperature in section 4.4.1. Table A.2 indicates the daily minimum, maximum and average outdoor temperature in May obtained from the input weather file. This was used to determine the hottest day in the year and to calculate the prevailing mean outdoor air temperature in acceptable limits of operating temperature in section 4.4.1.

Table A.1: Monthly average temperatures in weather file

Month	Outside temperature (^0C)
January	26.75
February	26.85
March	27.83
April	28.34
May	28.42
June	27.9
July	27.55
August	27.44
September	27.26
October	27.01
November	26.57
December	26.39

Table A.2: Monthly average temperatures in weather file

Day	Minimum (^0C)	Maximum (^0C)	Average (^0C)
1	25.1	29.5	27.30
2	25.23	32.2	28.72
3	26.17	32.35	29.26
4	26.33	32.33	29.33
5	25.08	32.45	28.77
6	26.23	32.38	29.31
7	26.13	31.98	29.06
8	26.48	31.98	29.23
9	26.38	32.78	29.58
10	25.08	31.45	28.27
11	26.25	30	28.13
12	25.85	32.8	29.33
13	26.05	30.85	28.45
14	25.1	31.7	28.40
15	25.3	31.75	28.53
16	25.42	31.58	28.50
17	25.05	31.67	28.36
18	24.48	30	27.24
19	23.8	31.2	27.50
20	24.1	30.33	27.22
21	25.1	32	28.55
22	28.1	31.95	30.03
23	24.92	31.98	28.45
24	23.98	31.25	27.62
25	24.63	27.85	26.24
26	26	31.77	28.89
27	27.08	32	29.54
28	26	31.77	28.89
29	25.23	28.73	26.98
30	27.42	30.3	28.86
31	27.4	28.95	28.18

APPENDIX B

Required velocities to achieve acceptable comfort levels

The required velocities to achieve 90% acceptable limits and 80% acceptable limits of operative temperature for each hour in May 22^{nd} is presented in table B.1.

Table B.1: Required velocities to achieve acceptable comfort levels

Time	Operative Temperature (^0C)	90% acceptable velocity (m/s)	80% acceptable velocity (m/s)
1:00:00 AM	29	0.3	0.3
2:00:00 AM	28.95	0.3	0.3
3:00:00 AM	28.83	0.3	0.3
4:00:00 AM	28.69	0.3	0.3
5:00:00 AM	28.55	0.3	0.3
6:00:00 AM	28.48	0.3	0.3
7:00:00 AM	28.48	0.3	0.3
8:00:00 AM	28.56	0.3	0.3
9:00:00 AM	28.77	0.3	0.3
10:00:00 AM	29.01	0.3	0.3
11:00:00 AM	29.48	0.6	0.3
12:00:00 PM	30.06	0.6	0.3
1:00:00 PM	30.58	0.9	0.6
2:00:00 PM	30.99	0.9	0.6
3:00:00 PM	31.29	1.2	0.6
4:00:00 PM	31.32	1.2	0.6
5:00:00 PM	31.33	1.2	0.6
6:00:00 PM	31.27	1.2	0.6
7:00:00 PM	30.94	0.9	0.6
8:00:00 PM	30.54	0.9	0.6
9:00:00 PM	30.19	0.6	0.3
10:00:00 PM	29.85	0.6	0.3
11:00:00 PM	29.51	0.6	0.3
12:00:00 AM	29.16	0.3	0.3

APPENDIX C

Energy scores calculated for hypothetical scenarios

The final score for each scenarios is presented from table C.1 to table C.6.

Table C.1: Values used for hypothetical scenarios

Scenario	Energy consumption		Energy source	SI	Normalised rates			Score
	Modeled	Actual			BC_{rate}	OB_{rate}	ES_{rate}	
1	3.85	48	100% grid	39.51	100	100	0	68
2	3.85	48	75% grid 25% solar	46.88	100	100	25	76
3	3.85	48	50% grid 50% solar	54.56	100	100	51	84.32
4	3.85	48	25% grid 75% solar	61.23	100	100	73.65	91.568
5	3.85	48	100% solar	69	100	100	100	100
6	3.85	73	100% grid	39.51	100	90.3	0	64.896
7	3.85	73	75% grid 25% solar	46.88	100	90.3	25	72.896
8	3.85	73	50% grid 50% solar	54.56	100	90.3	51	81.216
9	3.85	73	25% grid 75% solar	61.23	100	90.3	73.65	88.464
10	3.85	73	100% solar	69	100	90.3	100	96.896
11	3.85	90	100% grid	39.51	100	83.7	0	62.784
12	3.85	90	75% grid 25% solar	46.88	100	83.7	25	70.784
13	3.85	90	50% grid 50% solar	54.56	100	83.7	51	79.104
14	3.85	90	25% grid 75% solar	61.23	100	83.7	73.65	86.352
15	3.85	90	100% solar	69	100	83.7	100	94.784
1	3.85	48	100% grid	39.51	100	100	30	77.6
2	3.85	48	75% grid 25% solar	46.88	100	100	47	83.04
3	3.85	48	50% grid 50% solar	54.56	100	100	66	89.12
4	3.85	48	25% grid 75% solar	61.23	100	100	82	94.24
5	3.85	48	100% solar	69	100	100	100	100
6	3.85	73	100% grid	39.51	100	90.3	30	74.496
7	3.85	73	75% grid 25% solar	46.88	100	90.3	47	79.936
8	3.85	73	50% grid 50% solar	54.56	100	90.3	66	86.016
9	3.85	73	25% grid 75% solar	61.23	100	90.3	82	91.136
10	3.85	73	100% solar	69	100	90.3	100	96.896
11	3.85	90	100% grid	39.51	100	83.7	30	72.384
12	3.85	90	75% grid 25% solar	46.88	100	83.7	47	77.824
13	3.85	90	50% grid 50% solar	54.56	100	83.7	66	83.904
14	3.85	90	25% grid 75% solar	61.23	100	83.7	82	89.024
15	3.85	90	100% solar	69	100	83.7	100	94.784

Table C.2: Values used for hypothetical scenarios Cont..

Scenario	Energy consumption		Energy source	SI	Normalised rates			Score
	Modeled	Actual			BC_{rate}	OB_{rate}	ES_{rate}	
16	3.85	120	100% grid	39.51	100	72.1	30	68
17	3.85	120	75% grid 25% solar	46.88	100	72.1	47	74.112
18	3.85	120	50% grid 50% solar	54.56	100	72.1	66	80.192
19	3.85	120	25% grid 75% solar	61.23	100	72.1	82	85.312
20	3.85	120	100% solar	69	100	72.1	100	91.072
21	3.85	180	100% grid	39.51	100	48.8	30	68
22	3.85	180	75% grid 25% solar	46.88	100	48.8	47	66.656
23	3.85	180	50% grid 50% solar	54.56	100	48.8	66	72.736
24	3.85	180	25% grid 75% solar	61.23	100	48.8	82	77.856
25	3.85	180	100% solar	69	100	48.8	100	83.616
26	3.85	306	100% grid	39.51	100	0	30	68
27	3.85	306	75% grid 25% solar	46.88	100	0	47	51.04
28	3.85	306	50% grid 50% solar	54.56	100	0	66	57.12
29	3.85	306	25% grid 75% solar	61.23	100	0	82	62.24
30	3.85	306	100% solar	69	100	0	100	68
31	10	48	100% grid	39.51	34.5	100	30	54.02
32	10	48	75% grid 25% solar	46.88	34.5	100	47	59.46
33	10	48	50% grid 50% solar	54.56	34.5	100	66	65.54
34	10	48	25% grid 75% solar	61.23	34.5	100	82	70.66
35	10	48	100% solar	69	34.5	100	100	76.42
36	10	73	100% grid	39.51	34.5	90.3	30	50.916
37	10	73	75% grid 25% solar	46.88	34.5	90.3	47	56.356
38	10	73	50% grid 50% solar	54.56	34.5	90.3	66	62.436
39	10	73	25% grid 75% solar	61.23	34.5	90.3	82	67.556
40	10	73	100% solar	69	34.5	90.3	100	73.316
41	10	90	100% grid	39.51	34.5	83.7	30	48.804
42	10	90	75% grid 25% solar	46.88	34.5	83.7	47	54.244
43	10	90	50% grid 50% solar	54.56	34.5	83.7	66	60.324
44	10	90	25% grid 75% solar	61.23	34.5	83.7	82	65.444
45	10	90	100% solar	69	34.5	83.7	100	71.204

Table C.3: Values used for hypothetical scenarios Cont..

Scenario	Energy consumption		Energy source	SI	Normalised rates			Score
	Modeled	Actual			BC_{rate}	OB_{rate}	ES_{rate}	
46	10	120	100% grid	39.51	34.5	72.1	30	45.092
47	10	120	75% grid 25% solar	46.88	34.5	72.1	47	50.532
48	10	120	50% grid 50% solar	54.56	34.5	72.1	66	56.612
49	10	120	25% grid 75% solar	61.23	34.5	72.1	82	61.732
50	10	120	100% solar	69	34.5	72.1	100	67.492
51	10	180	100% grid	39.51	34.5	48.8	30	37.636
52	10	180	75% grid 25% solar	46.88	34.5	48.8	47	43.076
53	10	180	50% grid 50% solar	54.56	34.5	48.8	66	49.156
54	10	180	25% grid 75% solar	61.23	34.5	48.8	82	54.276
55	10	180	100% solar	69	34.5	48.8	100	60.036
56	10	306	100% grid	39.51	34.5	0	30	22.02
57	10	306	75% grid 25% solar	46.88	34.5	0	47	27.46
58	10	306	50% grid 50% solar	54.56	34.5	0	66	33.54
59	10	306	25% grid 75% solar	61.23	34.5	0	82	38.66
60	10	306	100% solar	69	34.5	0	100	44.42
61	30	48	100% grid	39.51	7.15	100	30	44.174
62	30	48	75% grid 25% solar	46.88	7.15	100	47	49.614
63	30	48	50% grid 50% solar	54.56	7.15	100	66	55.694
64	30	48	25% grid 75% solar	61.23	7.15	100	82	60.814
65	30	48	100% solar	69	7.15	100	100	66.574
66	30	73	100% grid	39.51	7.15	90.3	30	41.07
67	30	73	75% grid 25% solar	46.88	7.15	90.3	47	46.51
68	30	73	50% grid 50% solar	54.56	7.15	90.3	66	52.59
69	30	73	25% grid 75% solar	61.23	7.15	90.3	82	57.71
70	30	73	100% solar	69	7.15	90.3	100	63.47
71	30	90	100% grid	39.51	7.15	83.7	30	38.958
72	30	90	75% grid 25% solar	46.88	7.15	83.7	47	44.398
73	30	90	50% grid 50% solar	54.56	7.15	83.7	66	50.478
74	30	90	25% grid 75% solar	61.23	7.15	83.7	82	55.598
75	30	90	100% solar	69	7.15	83.7	100	61.358

Table C.4: Values used for hypothetical scenarios Cont..

Scenario	Energy consumption		Energy source	SI	Normalised rates			Score
	Modeled	Actual			BC_{rate}	OB_{rate}	ES_{rate}	
76	30	120	100% grid	39.51	7.15	72.1	30	35.246
77	30	120	75% grid 25% solar	46.88	7.15	72.1	47	40.686
78	30	120	50% grid 50% solar	54.56	7.15	72.1	66	46.766
79	30	120	25% grid 75% solar	61.23	7.15	72.1	82	51.886
80	30	120	100% solar	69	7.15	72.1	100	57.646
81	30	180	100% grid	39.51	7.15	48.8	30	27.79
82	30	180	75% grid 25% solar	46.88	7.15	48.8	47	33.23
83	30	180	50% grid 50% solar	54.56	7.15	48.8	66	39.31
84	30	180	25% grid 75% solar	61.23	7.15	48.8	82	44.43
85	30	180	100% solar	69	7.15	48.8	100	50.19
86	30	306	100% grid	39.51	7.15	0	30	12.174
87	30	306	75% grid 25% solar	46.88	7.15	0	47	17.614
88	30	306	50% grid 50% solar	54.56	7.15	0	66	23.694
89	30	306	25% grid 75% solar	61.23	7.15	0	82	28.814
90	30	306	100% solar	69	7.15	0	100	34.574
91	50	48	100% grid	39.51	1.68	100	30	42.2048
92	50	48	75% grid 25% solar	46.88	1.68	100	47	47.6448
93	50	48	50% grid 50% solar	54.56	1.68	100	66	53.7248
94	50	48	25% grid 75% solar	61.23	1.68	100	82	58.8448
95	50	48	100% solar	69	1.68	100	100	64.6048
96	50	73	100% grid	39.51	1.68	90.3	30	39.1008
97	50	73	75% grid 25% solar	46.88	1.68	90.3	47	44.5408
98	50	73	50% grid 50% solar	54.56	1.68	90.3	66	50.6208
99	50	73	25% grid 75% solar	61.23	1.68	90.3	82	55.7408
100	50	73	100% solar	69	1.68	90.3	100	61.5008
101	50	90	100% grid	39.51	1.68	83.7	30	36.9888
102	50	90	75% grid 25% solar	46.88	1.68	83.7	47	42.4288
103	50	90	50% grid 50% solar	54.56	1.68	83.7	66	48.5088
104	50	90	25% grid 75% solar	61.23	1.68	83.7	82	53.6288
105	50	90	100% solar	69	1.68	83.7	100	59.3888

Table C.5: Values used for hypothetical scenarios Cont..

Scenario	Energy consumption		Energy source	SI	Normalised rates			Score
	Modeled	Actual			BC_{rate}	OB_{rate}	ES_{rate}	
106	50	120	100% grid	39.51	1.68	72.1	30	33.2768
107	50	120	75% grid 25% solar	46.88	1.68	72.1	47	38.7168
108	50	120	50% grid 50% solar	54.56	1.68	72.1	66	44.7968
109	50	120	25% grid 75% solar	61.23	1.68	72.1	82	49.9168
110	50	120	100% solar	69	1.68	72.1	100	55.6768
111	50	180	100% grid	39.51	1.68	48.8	30	25.8208
112	50	180	75% grid 25% solar	46.88	1.68	48.8	47	31.2608
113	50	180	50% grid 50% solar	54.56	1.68	48.8	66	37.3408
114	50	180	25% grid 75% solar	61.23	1.68	48.8	82	42.4608
115	50	180	100% solar	69	1.68	48.8	100	48.2208
116	50	306	100% grid	39.51	1.68	0	30	10.2048
117	50	306	75% grid 25% solar	46.88	1.68	0	47	15.6448
118	50	306	50% grid 50% solar	54.56	1.68	0	66	21.7248
119	50	306	25% grid 75% solar	61.23	1.68	0	82	26.8448
120	50	306	100% solar	69	1.68	0	100	32.6048
121	62.892	48	100% grid	39.51	0	100	30	41.6
122	62.892	48	75% grid 25% solar	46.88	0	100	47	47.04
123	62.892	48	50% grid 50% solar	54.56	0	100	66	53.12
124	62.892	48	25% grid 75% solar	61.23	0	100	82	58.24
125	62.892	48	100% solar	69	0	100	100	64
126	62.892	73	100% grid	39.51	0	90.3	30	38.496
127	62.892	73	75% grid 25% solar	46.88	0	90.3	47	43.936
128	62.892	73	50% grid 50% solar	54.56	0	90.3	66	50.016
129	62.892	73	25% grid 75% solar	61.23	0	90.3	82	55.136
130	62.892	73	100% solar	69	0	90.3	100	60.896
131	62.892	90	100% grid	39.51	0	83.7	30	36.384
132	62.892	90	75% grid 25% solar	46.88	0	83.7	47	41.824
133	62.892	90	50% grid 50% solar	54.56	0	83.7	66	47.904
134	62.892	90	25% grid 75% solar	61.23	0	83.7	82	53.024
135	62.892	90	100% solar	69	0	83.7	100	58.784

Table C.6: Values used for hypothetical scenarios Cont..

Scenario	Energy consumption		Energy source	SI	Normalised rates			Score
	Modeled	Actual			BC_{rate}	OB_{rate}	ES_{rate}	
136	62.892	120	100% grid	39.51	0	72.1	30	32.672
137	62.892	120	75% grid 25% solar	46.88	0	72.1	47	38.112
138	62.892	120	50% grid 50% solar	54.56	0	72.1	66	44.192
139	62.892	120	25% grid 75% solar	61.23	0	72.1	82	49.312
140	62.892	120	100% solar	69	0	72.1	100	55.072
141	62.892	180	100% grid	39.51	0	48.8	30	25.216
142	62.892	180	75% grid 25% solar	46.88	0	48.8	47	30.656
143	62.892	180	50% grid 50% solar	54.56	0	48.8	66	36.736
144	62.892	180	25% grid 75% solar	61.23	0	48.8	82	41.856
145	62.892	180	100% solar	69	0	48.8	100	47.616
146	62.892	306	100% grid	39.51	0	0	30	9.6
147	62.892	306	75% grid 25% solar	46.88	0	0	47	15.04
148	62.892	306	50% grid 50% solar	54.56	0	0	66	21.12
149	62.892	306	25% grid 75% solar	61.23	0	0	82	26.24
150	62.892	306	100% solar	69	0	0	100	32

APPENDIX D

Questionnaires

This section includes the two main questionnaires used for the research. The first questionnaire includes the consumer survey which was used for identifying the consumer behaviour and patterns and the second questionnaire is used for analysing the Solar PV consumer behaviour.

Reference No :______________________

Energy consumption survey

This survey is being conducted for research at the Department of Civil Engineering, University of Moratuwa. The study focuses on the energy use of Sri Lankan households and the consumption patterns. The results will be used for a postgraduate student research and the information you provide will remain anonymous.
The survey will take 5 to 10 minutes. Please answer all the questions to the best of your ability and thank you for your cooperation.

GENERAL INFORMATION

1. Location

District ____________________

Town ____________________

2. Average electricity consumption

Bill value Rs. ____________________

Number of units ____________

3. Description about the members of household

Member	**Age** **(approximate)**	**Employment status** Employed **(E)** / Student **(S)** / Stay at home **(SH)**
1		
2		
3		
4		
5		
6		
7		

BUILDING INFORMATION

4. Shape of the house

☐ Square
☐ Rectangle
☐ T shape
☐ L shape
☐ Other shape

5. Number of floors

☐ 1
☐ 2
☐ 3
☐ 4
☐ 5

6. Number of bedrooms (Including visitors' rooms)

☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ 6
☐ More than 6

7. Ventilation and cooling method

☐ Natural ventilation (without fans)
☐ Natural ventilation with fans
☐ Air conditioning (all areas)
☐ Air conditioning (few areas - please mention the areas)
  ☐ Bedrooms _________ (no of A/C bedrooms)
  ☐ Living
  ☐ Other ________________________________

8. Total floor area of the house (If known)

____

OCCUPANCY SCHEDULES

9. Average occupancy time at home (considering **majority** the members of home)

Eg. If you leave home at 7.00 am for work and come back home at 6.00 pm

Leave	Return
7.00 am	6.00 pm

Day	**Leave**	**Return**
Week day		
Saturday		
Sunday		

10. Average Door / Window opening schedules

Door / Window	**Opening time**	**Closing time**
Main Door		
Windows		

11. Average lighting schedules

Time	**Switch on light**	**Switch off light**
Night		
Morning		

EQUIPMENT USAGE

12. **Frequently used** electric equipment

☐ Refrigerator (☐ mini / ☐ 1 door / ☐ 2 door / ☐ large)
☐ Fans (☐ Ceiling / ☐ Standing / ☐ Table)
☐ Computer (☐ Desktop / ☐ Laptop)
☐ Television (☐ CRT / ☐ LED or ☐ LCD)
☐ Bulbs (☐ LED / ☐ CFL / ☐ Incandescent)
☐ Other ____

☐ Washing machine
☐ Hot water bath or shower
☐ Electric kettle
☐ Electric iron
☐ Electric car

Thank you for your cooperation.

Solar Photovoltaic (PV) Household Survey

This survey is being conducted for research at the Department of Civil Engineering, University of Moratuwa. The study focuses on Sri Lankan households with solar photovoltaic and their use of energy. The results will be used for a postgraduate student research and the information you provide will remain anonymous.

The survey is to be completed by the head of the household and should take 10 to 15 minutes. Please answer all the questions to the best of your ability and thank you for your cooperation.

* Required

1. General Details

1.1. District of the solar installed property ___________________________

1.2. How many people, including yourself, live in your house? * __________

1.3. What is the composition of your household? Select all the relevant answers.
a) You b) Spouse c) Parents d) Siblings e) Children

1.4. What is the age group of your children? _________________

1.5. How long have you lived in this house? __________________

2. Solar Installation Details

2.1. When did you install the solar panel? * ___________________

2.2. How did you select the solar panel capacity? *
- a) You decided by yourself to match your consumption
- b) You took the advice from the solar company
- c) You took the advice from another person
- d) Other

2.3. What is the existing capacity of the solar panels you have installed? (Number of solar panels x panel capacity) _______________

2.4. What is the maximum capacity of the inverter? _______________

2.5. What is the payback period of your solar panels? * ______________

2.6. How did you finance the solar panels and installation? *
- a) You used cash in hand
- b) You took a solar power loan from bank
- c) You took a personal loan from a bank
- d) Other

2.7. What kind of energy storage model do you have?
- a) Net metering
- b) Net accounting
- c) Battery pack
- d) Net metering / Net accounting with battery pack

3. Energy Use at Home

3.1. How many units (average) did you consume before solar installation? _______________

3.2. What was your electricity cost (average) before solar installation? * _________________

3.3. How many units (average) do you consume now (total - from solar and grid)? * ________

3.4. How many excess units (average) do you supply to the main grid? _____________

3.5. Which of the following you had prior to solar installation?

a) Refrigerator
b) Television
c) Washing machine
d) Electric cooker
e) Electric oven
f) Microwave oven
g) Electric car
h) Air conditioning (A/C) unit
i) Hot water shower or bath (heated by electricity)
j) Other ______________________

3.6. Which of the following did you purchase for regular use after solar installation?

a) Refrigerator
b) Television
c) Washing machine
d) Electric cooker
e) Electric oven
f) Microwave oven
g) Electric car
h) Air conditioning (A/C) unit
i) Hot water shower or bath (heated by electricity)
j) Other __________________________

3.7. How do you spend the saved money due to the reduction in electricity bill?

a) You purchase energy consuming products.
b) You purchase non energy consuming products
c) You pay the bank loan (solar loan or personal loan)
d) You save the money for future uses
e) Other ____________________________

3.8. According to your opinion, what has caused the increase in electricity consumption in your house (select all applicable answers)

a) Increase in the number of members in the household
b) Decrease in the number of members in the household
c) Addition of any component in the house (eg. addition of room)
d) Removal of any component in the house (eg. removal of room)
e) Purchasing of new equipment
f) Electricity consumption did not increase
g) Other __________________________

3.9. What was your motivation in purchasing solar system?

a) To reduce the energy bill
b) To purchase additional energy consuming equipment without increasing energy bill
c) Since it is green energy
d) Since it is the fashion
e) Other ____________________

Thank you very much for your time