MASTERS PROJECT THESIS ON

PROCESS TO CONVERT AN EXISTING BUILDING INTO ZERO ENERGY BUILDING(ZEB) IN 3 CITIES (LONDON,PATRAS AND CHENNAI) : COMPARATIVE RESULTS

BY

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Abstract

This dissertation details the process for converting an existing building into a Zero Energy Building(ZEB) in 3 major cities namely London,Patras and Chennai located in the United Kingdom, Greece and India respectively.Initially,the overall Heat losses coefficient $(UA)_b$ is determined for the building in each one of the cities .Subsequently,the thermal Loads comprising Heating (Space Heating,Domestic hot water and Heat losses)and the Cooling loads for the building are determined through appropriate equations for the seasonal months(Jan,Apr,Jul,Oct). In addition,the electric loads of the building in the 3 cities are calculated.By the use of passive solar techniques which considers the solar gain through the windows , the thermal demand(Space Heating Load) of the building is reduced .To satisfy the thermal load demand through renewables ,solar collectors are considered and a daily hourly simulation is performed to calculate the collector output following which the area of the collectors required for different fraction of the loads is determined.The Heat Pump is sized for satisfying the cooling demand in Chennai.A stand alone PV system is designed to meet the electric Loads .In addition,an important comparison is made between the 2 approaches used to calculate the Space Heating Load and the 2 approaches used for the sizing of the stand alone PV in the thesis.Finally,the dissertation concludes by performing an economic analysis to calculate the Net Present Value(NPV)and the Internal Rate of Return(IRR) for different fraction of thermal needs by Solar Collector to determine the scenario with most economic feasibility.

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Chapter 1

1.1 Zero Energy Buildings (Definitions)

Net-Zero Energy Buildings (NZEBs) are buildings which, on an annual basis, use no more energy than is provided by on-site renewable energy sources (ASHRAE). There are several ways by which Zero Energy Buildings can be defined which are enlisted below (adopted from U.S DOE Solar Decathlon 2009).

Net zero site energy use

In this type of ZEB, the amount of energy provided by on-site renewable energy sources is equal to the amount of energy used by the building.

Net zero source energy use

This ZEB generates the same amount of energy as is used, including the energy used to transport the energy to the building. This type accounts for losses during electricity transmission. These ZEBs must generate more electricity than net zero site energy buildings.

Net zero energy emissions

Under this definition the carbon emissions generated from on-site or off-site fossil fuel use are balanced by the amount of on-site renewable energy production.

Net zero cost

The cost of purchasing energy is balanced by income from sales of electricity to the grid of electricity generated on-site .

Net off-site zero energy use

A building may be considered a ZEB if 100% of the energy it purchases comes from renewable energy sources, even if the energy is generated off the site.

Off-the-grid

Off-the-grid buildings are stand-alone ZEBs that are not connected to an off-site energy utility facility. They require distributed renewable energy generation and energy storage capability .

1.2 Introduction

Buildings account for a significant proportion of the total energy and carbon emissions worldwide, and play an important role in formulating sustainable development strategies. There is a growing interest in ZEBs(zero energy buildings) in recent years [*Danny et al,2013*] Energy consumed in-buildings accounts for 40% of the energy used worldwide, and measures and changes in the building modus operandi can yield substantial savings in energy. Moreover buildings nowadays are increasingly expected to meet higher and potentially more complex levels of performance. They should be sustainable, use zero-net energy, be healthy and comfortable, grid-friendly, yet economical to build and maintain [*D. Kolokotsa et al,2011*].

Fig.1-1 shows that a major consumption of energy in residential homes is because of Heating Systems/Electric Boilers(18.7%) used for the purpose of Space Heating and Hot water.

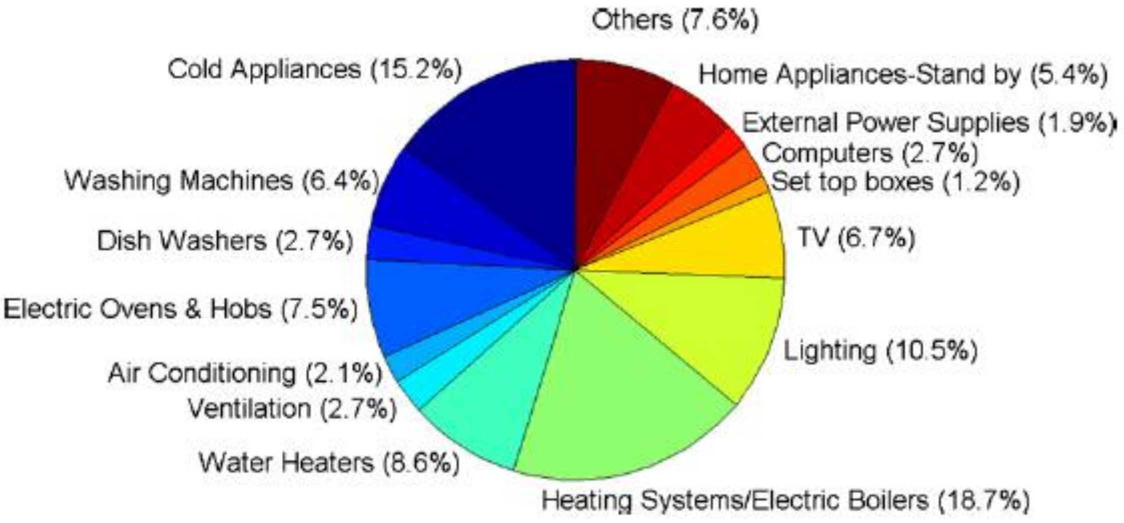


Figure 1-1: Breakdown of EU residential electricity consumption,2007

(Source : Ferrantea et al.2011)

The topic of zero energy buildings (ZEBs) has received increasing attention in recent years, until becoming part of the energy policy in several countries. In the recast of the EU Directive on Energy Performance of Buildings (EPBD), it is specified that by the end of 2020 all new buildings shall be “nearly zero energy buildings”[*EPBD recast, Directive 2010/31/EU*]. For the Building Technologies Program of the US Department of Energy (DOE), the strategic goal is to achieve "marketable zero energy homes in 2020 and commercial zero energy buildings in 2025"[*US DOE*].

Fig.1-2 shows the locations of Net Zero Energy Buildings(nZEB) worldwide. It can be noticed from Fig.1-2 that there is a high concentration of nZEBs particularly in North America and Western Europe .

Figure 1-2:World-wide locations of nZEB

(Source :IEA HPT Annex 40)

Zero Net Energy Buildings are buildings that over a year are neutral, meaning that they deliver as much energy to the supply grids as they use from the grids. Seen in these terms they do not need any fossil fuel for heating, cooling, lighting or other energy uses although they sometimes draw energy from the grid (*Laustsen 2008*).Zero Energy Building (ZEB) concept is no longer perceived as a concept of a remote future, but as a realistic solution for the mitigation of CO_2 emissions and/or the reduction of energy use in the building sector*(Marszal et al.2013)*.ZEB is an energy efficient building able to generate electricity, or other energy carriers, from renewable sources in order to compensate for its energy demand. The term Net ZEB can be used to refer to buildings that are connected to the energy infrastructure, while the term ZEB is more general and includes autonomous buildings.

‘Net’ implies the fact that there is a balance between energy taken from and supplied back to the energy grids over a period of time, nominally a year.The objective of a NZEB is not only to minimize the energy consumption of the building with passive design methods, but also to design a building that balances energy requirements with active energy production techniques and renewable technologies (for example, BIPV, solar thermal or wind turbines).NZEB operation requires communication between many systems and elements that are of different type, serve different purposes as seen in Fig.1-3.

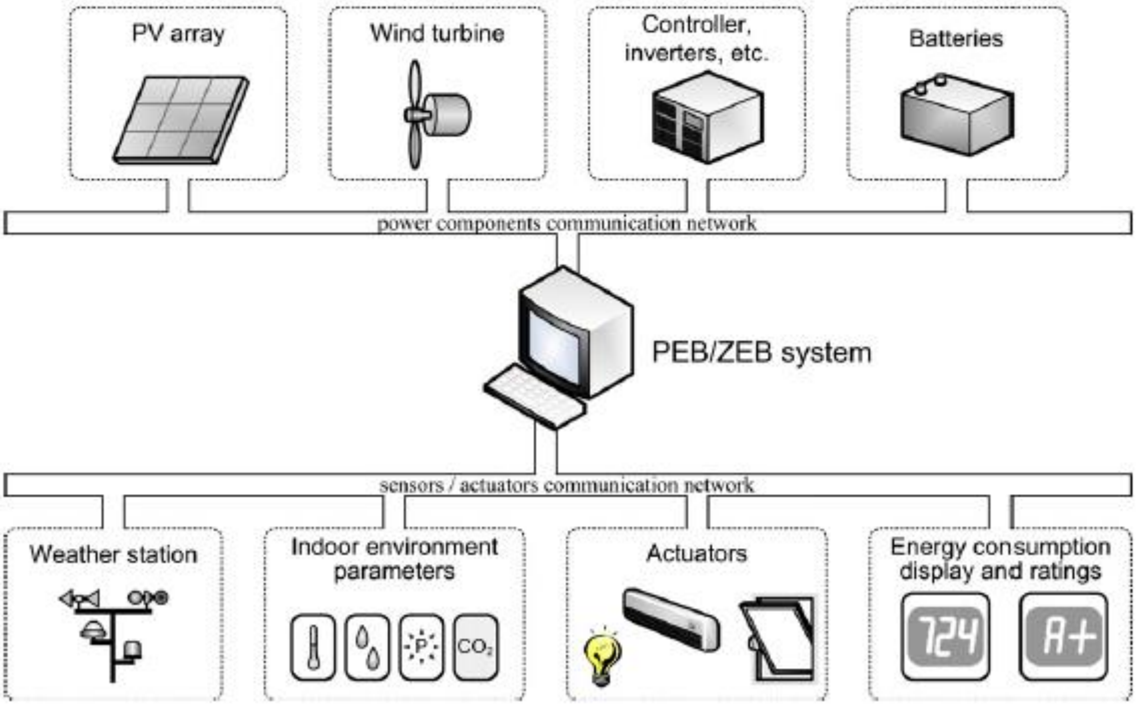


Figure 1-3:The monitoring and infrastructure of a ZEB/PEB system

(Source : Kolokotsa et al , 2011)

Chapter 2

LITERATURE REVIEW ON ZEB

The study of existing literature revealed that the lack of a commonly agreed ZEB definition is already widely discussed on the international level(*IEA SHC Task 40/ECBCS*). *Marszal et al.*(*2013*) in their paper have given an overview of existing ZEB definitions by highlighting the most important aspects which should be discussed before developing new ZEB definitions. In addition,they have also presented various approaches towards possible ZEB calculation methodologies. Their study indicated that the metric of the balance, the period and the types of energy included in the energy balance together with the renewable energy supply options, the connection to the energy infrastructure and energy efficiency, the indoor climate and the building–grid interaction requirements are the most important issues.

The definitions of ZEB require the use of a defined site boundary. The site boundary represents a meaningful boundary that is functionally part of the building(s). The site boundary for a Zero Energy Building (ZEB) could be around the building footprint if the on-site renewable energy is located within the building footprint, or around the building site if some of the on-site renewable energy is on-site but not within the building footprint. Delivered energy and exported energy are measured at the site boundary(*US DOE)*.Here,the term delivered energy signifies the energy delivered to the building from the grid and the exported energy refers to the excess energy generated by the renewables which is supplied to the grid .

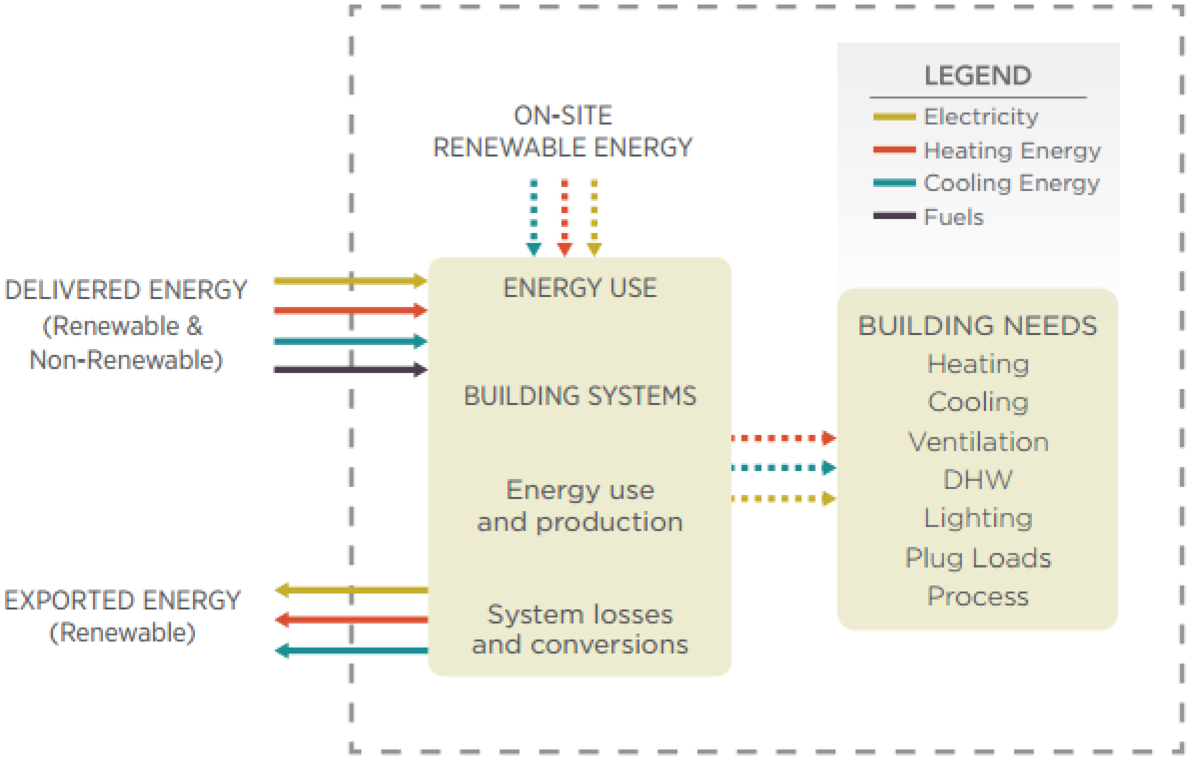


Figure 2-1: Site Boundary of Energy Transfer for Zero Energy Accounting

(Source :U.S. DOE 2015)

Danny et al.(2013) in “Zero energy buildings and sustainable development Implications” have categorized energy-efficient measures that have significant influence on energy consumption in buildings into 3 groups .

- Building envelopes - thermal insulation, thermal mass, windows/ glazing (including daylighting) and reflective/green roofs.
- Internal conditions - indoor design conditions and internal heat loads (due to electric lighting and equipment/appliances).
- Building services systems - HVAC (heating, ventilation and air conditioning), electrical services (including lighting) and vertical transportation (lifts and escalators).

In their work, they have also stated that the commonly used options to satisfy the energy demand in ZEBs by the use of onsite renewables (the first four are usually on-site and the last option is off-site) are :

- PV (Photovoltaic) and BIPV (building-integrated photovoltaic)
- Wind turbines

- Solar thermal (solar water heaters)
- Heat pumps
- District heating and cooling.

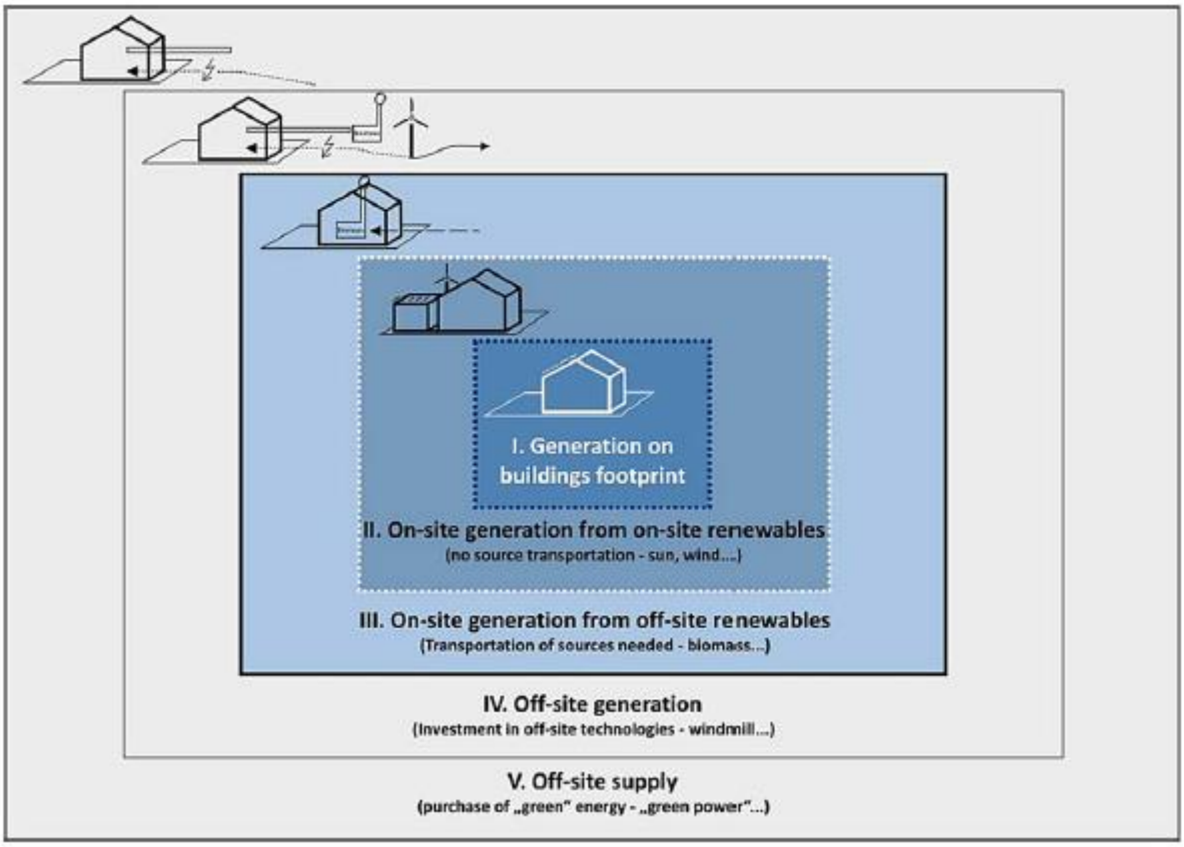


Figure 2-2:Overview of possible renewable supply options

(Source : Marszal et al.2011)

Fig.2-2 shows the different options available for accessing renewable energy and to satisfy the energy demand of the building throughout the year.

Kolokotsa et al.(2013) in their work have noted that “Buildings are complex systems and detailed simulation is needed to take into account the actual climate data, geometries, building physics, HVAC-systems, energy-generation systems, natural ventilation, user behaviour (occupancy, internal gains, manual shading), etc. towards a zero or positive energy approach”. In order to obtain an accurate simulation model, detailed representation of the building structure and the subsystems is required, but it is the integration of all the systems that requires significant effort.

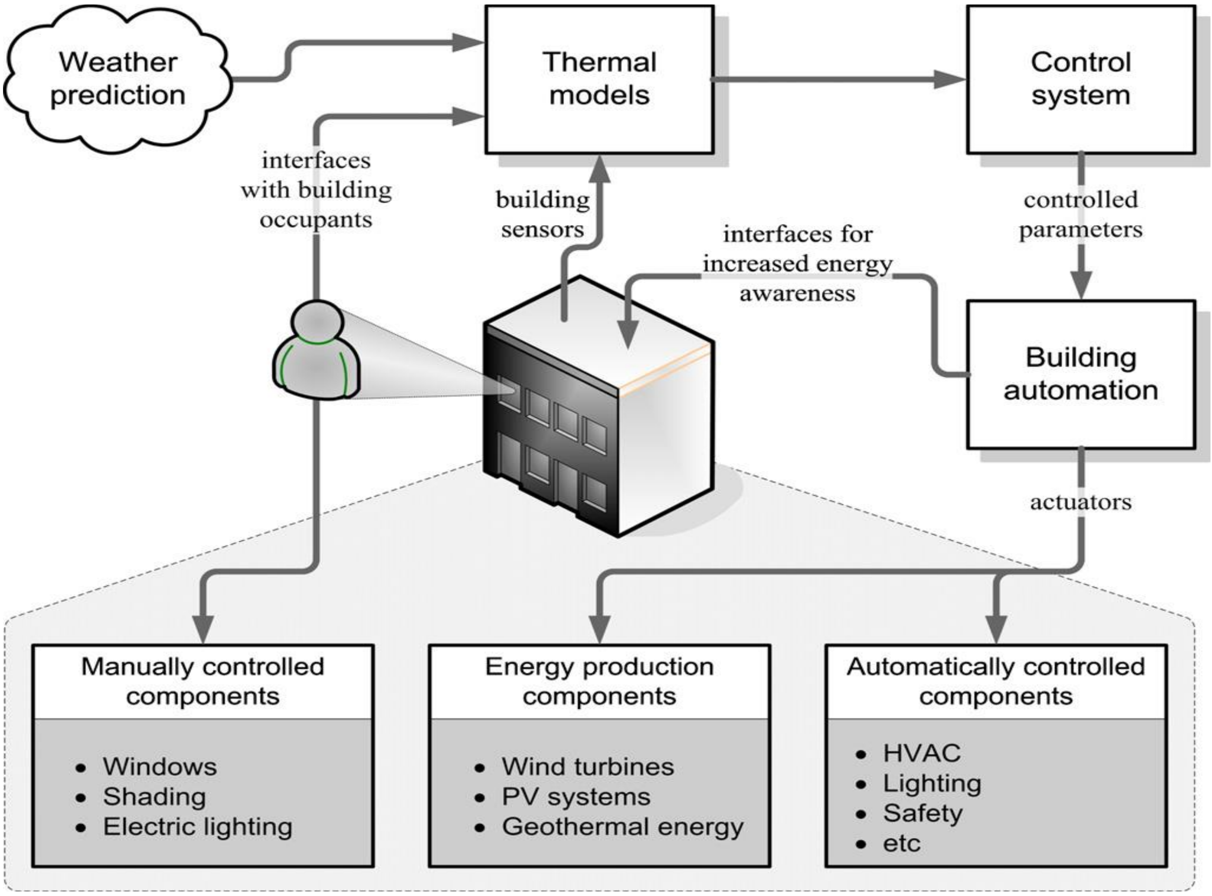


Figure 2-3:The components of a ZEB/PEB architecture during real-time operation

(Source :Kolokotsa et al.2013)

Fig.2-3 depicts the PEB/NZEB modeling, building automation components (i.e. infrastructure and networking) realtime optimization and control of PEB/NZEB operations and user-interaction .

Lund et al.(2010) examine the role of district Heating in future renewable energy systems in Denmark. Their study comprised about 25 per cent of the Danish building stock, which have individual gas or oil boilers and could be substituted by district heating or a more efficient individual heat source .They concluded that in such a perspective, the best option will be to combine a gradual expansion of district heating with individual heat pumps in the remaining buildings.

Wang et al.(2009) have made a case study of Zero Energy building design and discussed possible solutions for zero energy building design in UK.They summarized the entire design process into 3 major steps.First,an analysis of the prevailing local climatic conditions is essential to promote Zero Energy homes. Secondly, the application of passive design methods and advanced facade designs is required to minimize the load requirement from heating and cooling through building energy simulations. Finally, through the use of simulation software TRNSYS to investigate various energy efficient mechanical systems and renewable energy systems including photovoltaic, wind turbines and solar hot water system to enable system design optimizations.

Systems designed to supply a renewable source of electricity are indispensable in the delivery of zero energy building designs *(Wang et al.2009)* . The scheme of a grid connected renewable electricity system is shown in Fig. 2-4. It is comprised of PV, small wind turbines, inverters for PV and wind turbine (from AC to DC), a distribution board, meters for export and import connected to the grid, and electricity loads .

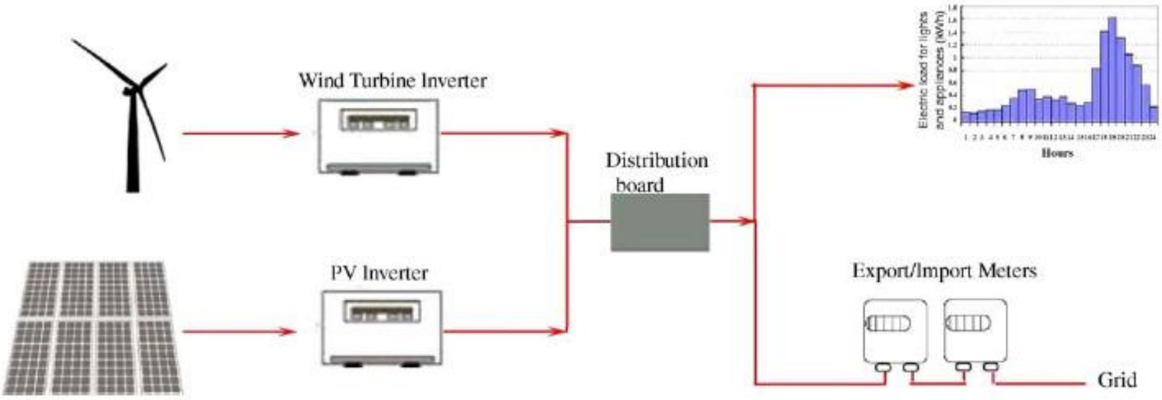


Figure 2-4 :Scheme of grid-connected renewable electricity system

(Source : Wang et al .2009)

A ZEB can be off-grid or on-grid. The main difference between those two approaches is that the off-grid ZEB is not connected to the utility grid, and thus it does not purchase energy from the external sources *(Voss et al.2007).* In other words, the building offset all required energy by producing energy from RES. The on-grid ZEB is also an energy producing building, but with the possibility of both purchasing energy from the grid and feeding excess energy production back to the grid to return as much energy to the utility as it uses on an annual basis *(Torcellini et al.2006).*

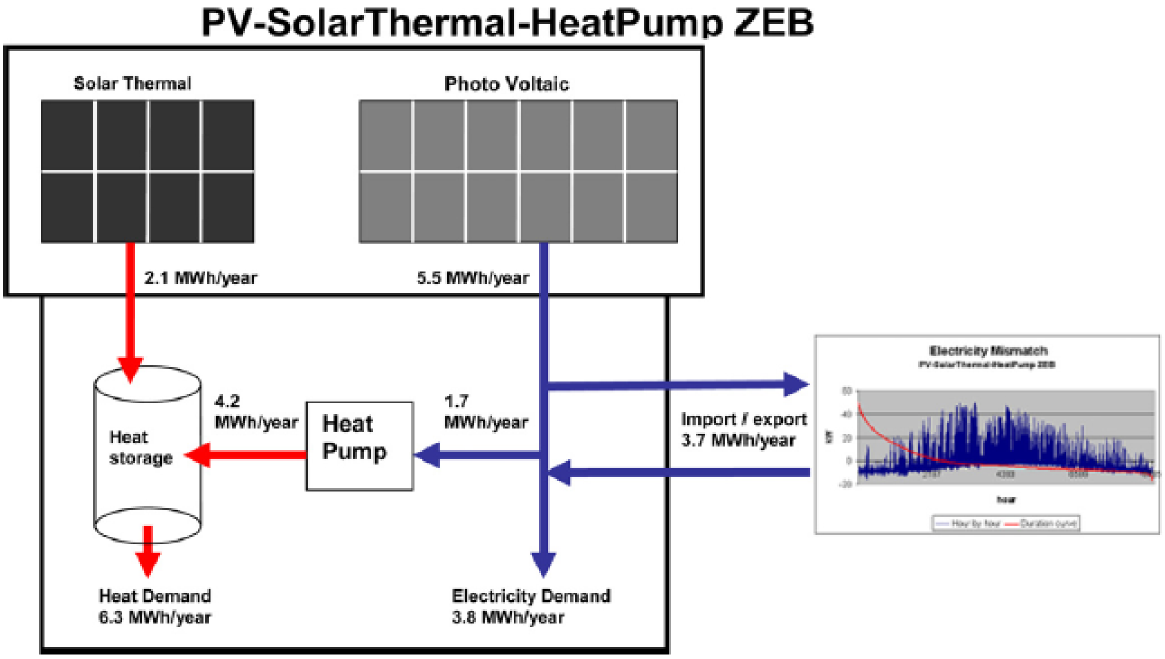


Figure 2-5: Principle diagram of the PV-SolarThermal-HeatPump ZEB

(Source: Lund et al .2011)

Fig.2-5 and 2-6 shows a grid connected ZEB with an expected annual net heat and electricity demand of zero but with a substantial exchange of electricity.The electric loads are met by Photo-Voltaic and Wind energy systems respectively with import/export from the grid during load deficit/load surplus respectively.

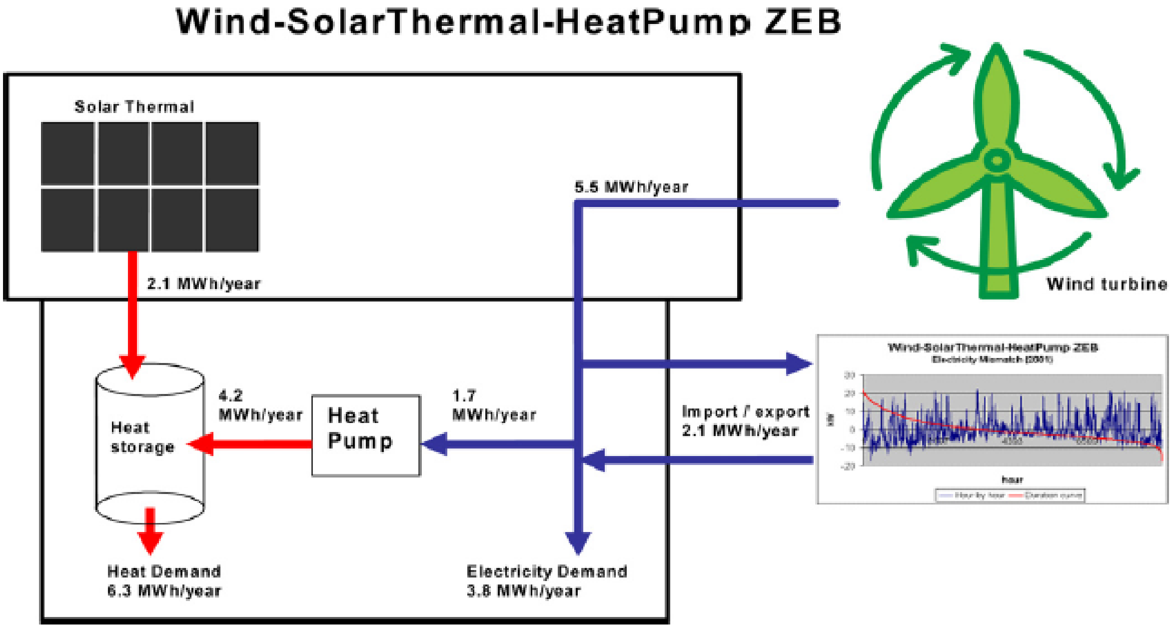


Figure 2-6: Principle diagram of the Wind-SolarThermal-HeatPump ZEB

(Source : Lund et al.2011)

Following the earlier paragraph,mismatches may occur from hourly differences in energy production and consumption at the building level. From the viewpoint of an overall electricity system,a mismatch can be positive or negative. *Lund et al.(2011)* in their work have argued the need to compensate the mismatch of a building by increasing (or decreasing) the capacity of the energy production unit . In order to quantify the mismatch, they defined four types of Zero energy buildings .

i) PV ZEB: Building with a relatively small electricity demand and a photovoltaic installation.
ii)Wind ZEB: Building with a relatively small electricity demand and a small on-site wind turbine.
iii) PV-SolarThermal-HeatPump ZEB: Building with a relatively small heat and electricity demand and a photovoltaic installation in combination with a solar thermal collector, a heat pump and heat storage.
iv)Wind-SolarThermal-HeatPump ZEB: Building with a relatively small heat and electricity demand and a wind turbine in combination with a solar thermal collector, a heat pump and heat storage.

Their study concluded that mismatch compensation factors are a little below one for buildings with photovoltaics (PV) and a little above one for buildings with wind turbines

Chapter 3

METEOROLOGICAL PARAMETERS – DATA

3.1 Climatic Conditions (India)

This Chapter presents the profiles of the Global Solar Radiation,hourly ambient Temperature that have an impact on the design of a ZEB.The climatic classification map of India is shown in Fig.3-1. Each climatic zone does not have same climate for the whole year. A climatic zone that does not have any season for more than six months may be called as composite zone.The nation has four seasons: winter (January and February), summer (March to May), a monsoon(rainy) season (June–September), and a post-monsoon period (October–December).The nation's climate is strongly influenced by the Himalayas and the Thar Desert [*Chang,1967*].

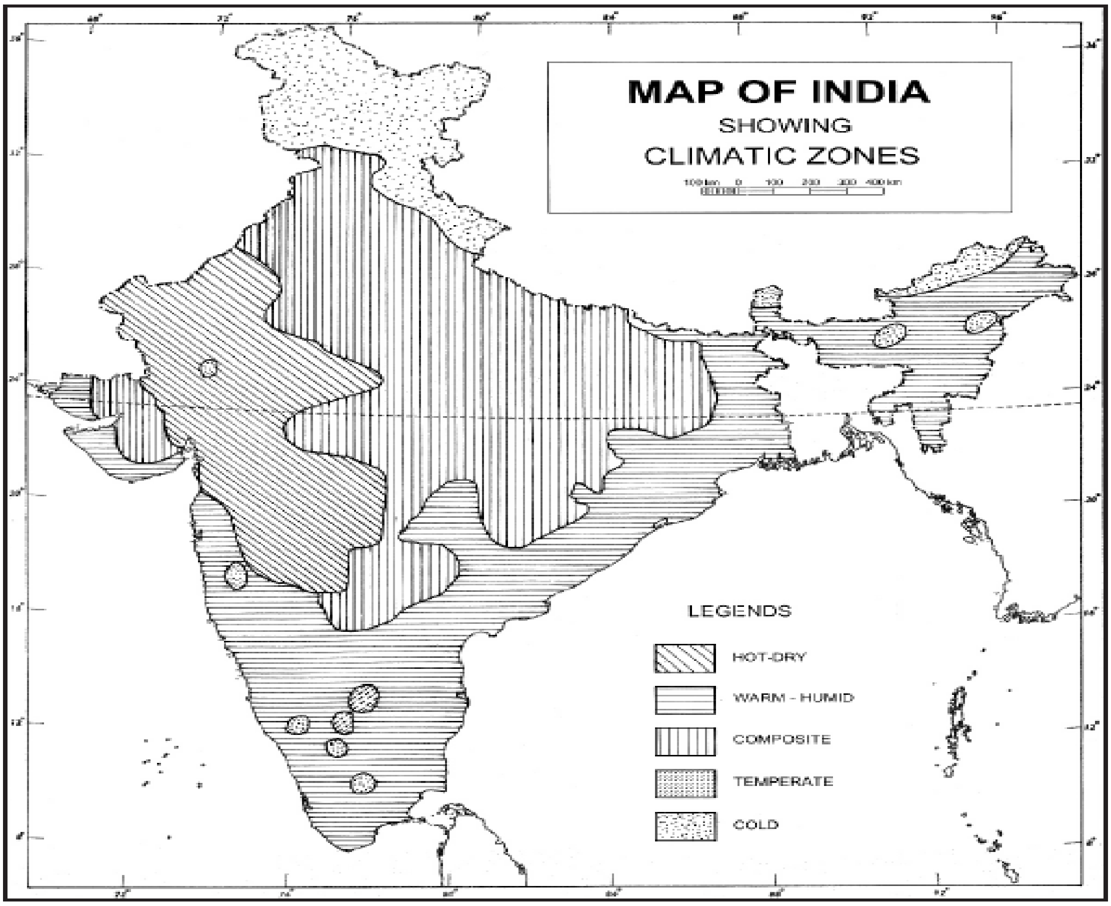


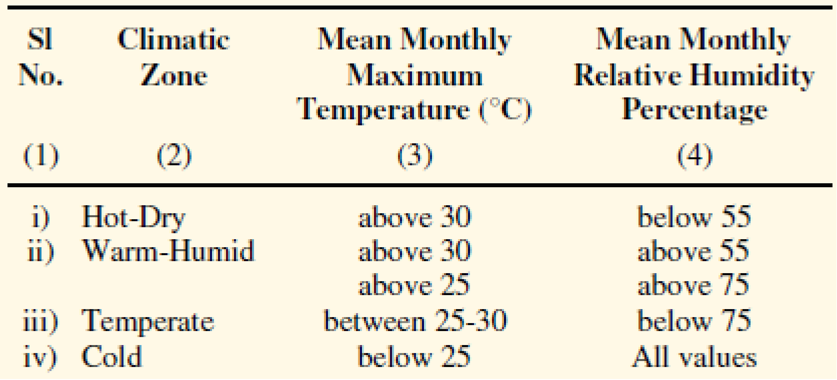
Figure 3-1: Map of India showing Climatic Zones(Based upon survey of India outline map printed in 1993)

(Source: National Building Code 2005)

For the purpose of design of buildings, the country may be divided into major climatic zones as given in Table 3-1.

Table 3-1 : Classification of Climatic Zones

(Source: National Building Code 2005)



Sl No. (1)	Climatic Zone (2)	Mean Monthly Maximum Temperature (°C) (3)	Mean Monthly Relative Humidity Percentage (4)
i)	Hot-Dry	above 30	below 55
ii)	Warm-Humid	above 30	above 55
		above 25	above 75
iii)	Temperate	between 25-30	below 75
iv)	Cold	below 25	All values

3.1.1 Solar Radiation and Temperature Profiles (Chennai)

Fig.3-2 depicts the average daily solar radiation profile on the horizontal for Chennai.

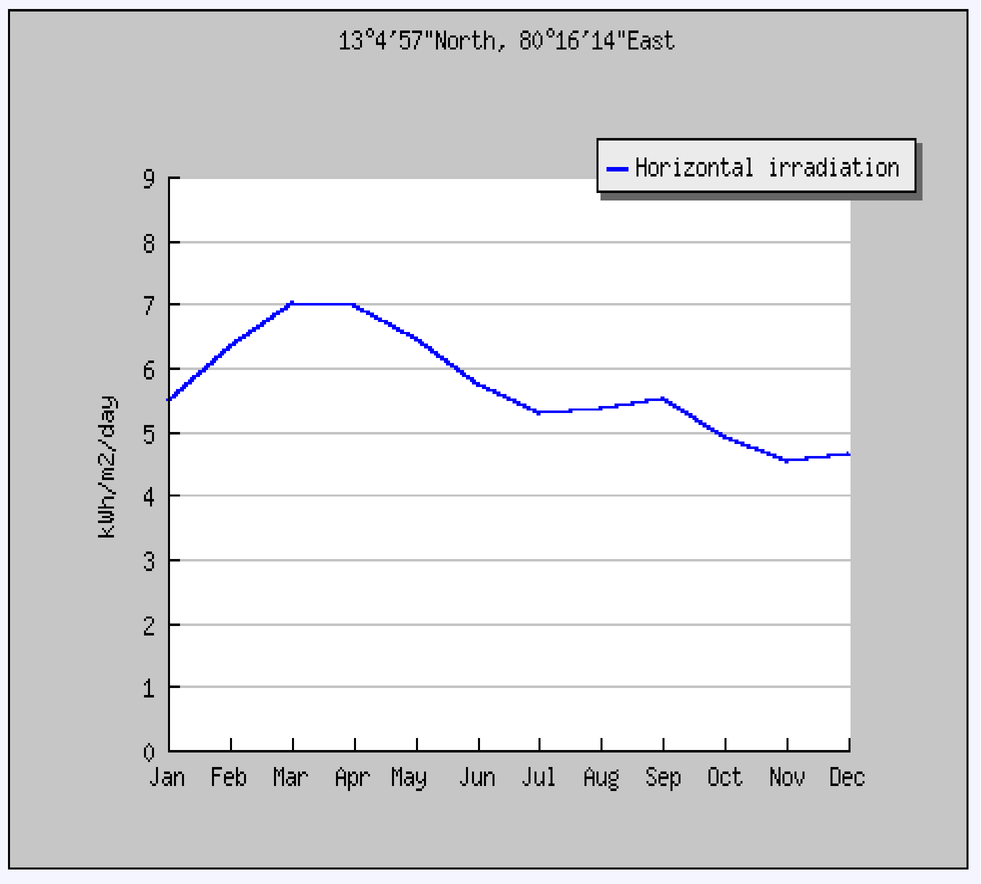


Figure 3-2: Horizontal Irradiation(average daily)for Chennai

(Source :PVGIS)

As observed from Fig.3-2,the city receives the maximum and the minimum average daily Solar Radiation Intensity on the Horizontal in March(**7.0kWh/m^2/day**)and November(**4.5 kWh/m^2/day**) respectively.

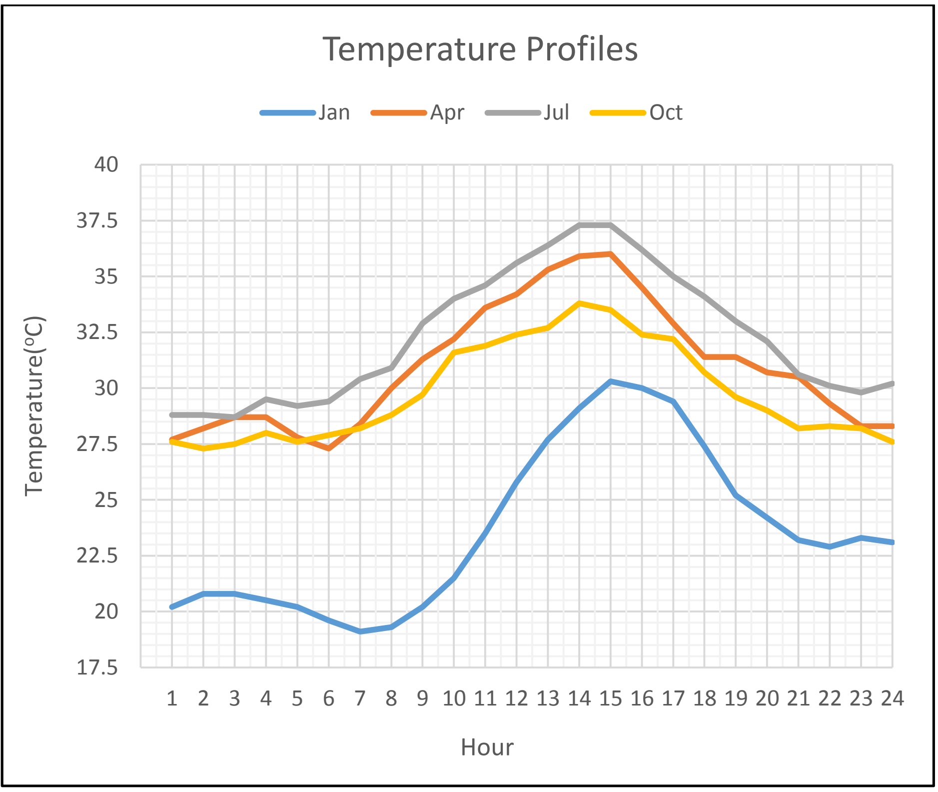


Figure 3-3:Hourly Ambient Temperature,T_a profiles on the Representative days of Seasonal months,Chennai

From Fig. 3-3,it can be inferred that the temperature around solar noon on the representative days is considerably higher than the temperatures at other hours .For the case of London and Patras temperature profiles are comparatively smoother as can be observed from Figs.3-5 & 3-9 respectively.

3.2 Climatic Conditions in England

England is situated to the west of Eurasia and has an extensive coastline. Such a positioning is responsible for its fairly complex climate, which demonstrates the meeting of the dry continental air and the moist maritime air. This creates rather large differences in temperature ranges and also leads to the occurrence of several seasons over the course of one day. The parts of England closest to the Atlantic Ocean experience the mildest temperatures, although these are also the wettest and experience the most wind. The areas in the east, on the other hand, are drier and less windy, but also display cooler temperatures. England is warmer and sunnier than any of the other countries making up the United Kingdom. The month with the most sunshine is July, which is also England's driest month.

3.2.1 Solar Radiation and Temperature Profiles (London)

The figures in this section depict the average daily solar radiation and hourly ambient temperature profiles of London which is located at geographical co-ordinates of 51.5° N and 0.127°W.

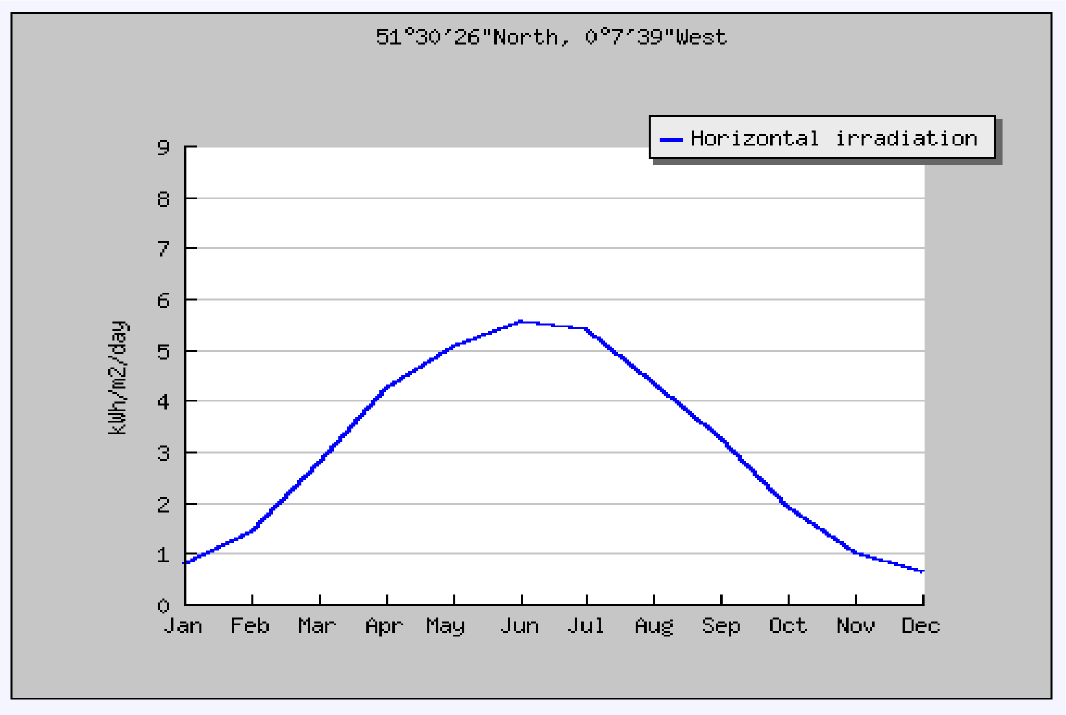


Figure 3-4:Horizontal Irradiation(average daily)for London

(Source :PVGIS)

From Fig.3-4,it can be noticed that London receives maximum and the minimum average daily Solar Radiation Intensity on the Horizontal in June (**5.5 kWh/m^2/day**)and in December(**0.64 kWh/m^2/day**) respectively.

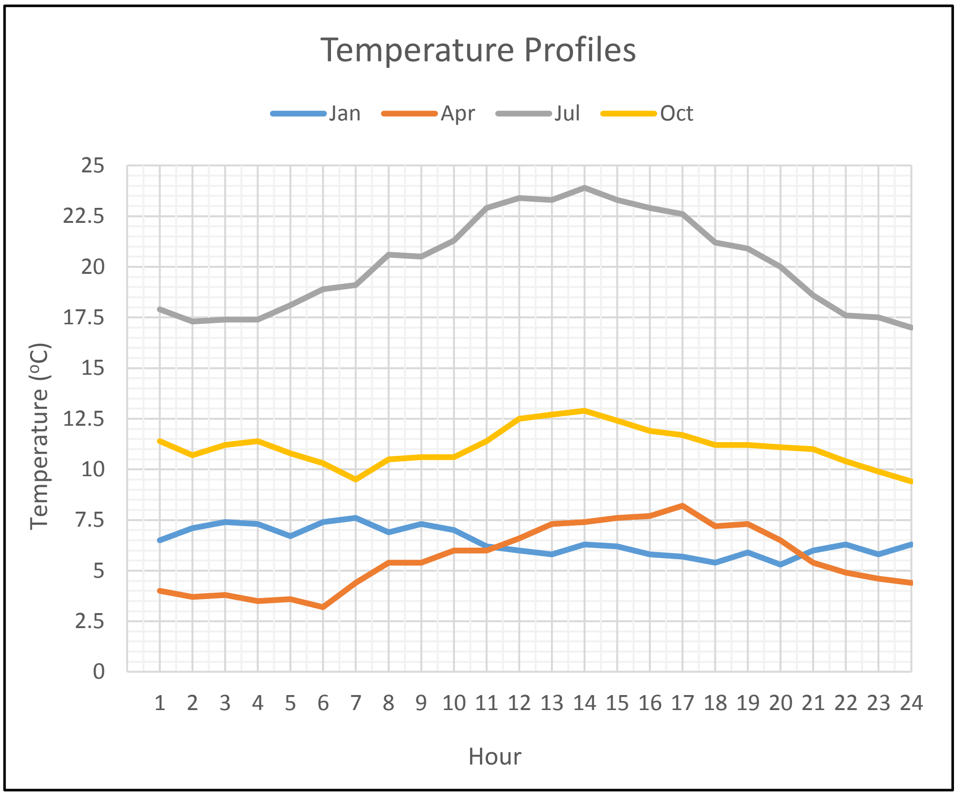


Figure 3-5:Hourly Ambient Temperature,T_a profiles on the Representative days of Seasonal months,London

3.3 Climatic Conditions in Greece

The climate of Greece is predominantly mediterranean with summers that are usually hot and dry, and the winters that can be quiet cold and wet. The upper part of Greece can be very cold during the winter. However, for the south of Greece and the islands, the winters will be milder.Figures 3-6 & 3-7 show the different climatic zones of Greece.

Figure 3-6:Climatic zones according to the existing thermal insulation regulation of 1979[13]

Figure 3-7:Climatic zones according to the new energy performance regulation(KENAK)[13]

3.3.1 Solar Radiation and Temperature Profiles

Figures in this section depict the average daily solar radiation and hourly ambient temperature profiles for Patras located at geographical co-ordinates of 38.25^{o}N and 21.73 ^{o}E.

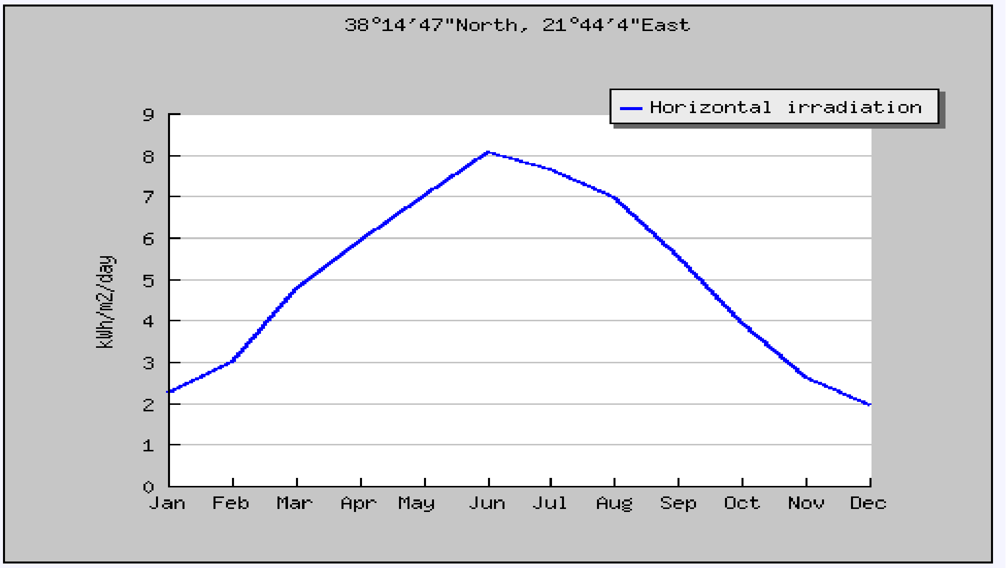


Figure 3-8:Horizontal Irradiation(average daily)for Patras

(Source : PVGIS)

From Fig.3-8 , June and December receive the maximum and the minimum average daily Solar Radiation Intensity on the Horizontal (**8.0 kWh/m^2/day**)and (**1.9 kWh/m^2/day**) respectively.

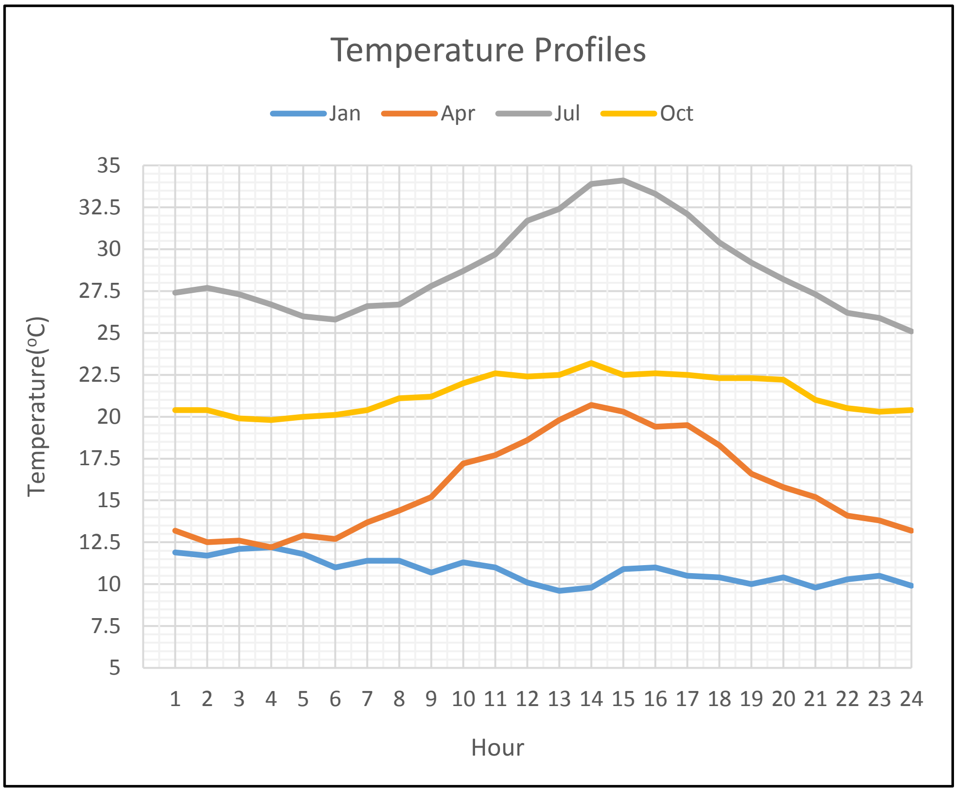


Figure 3-9: Hourly Ambient Temperature,T_a profiles on the Representative days of Seasonal months,Patras

There will be discussion in chapter 5 on how the hourly solar radiation intensity values and the hourly temperature values influence the calculation of the Solar gain into the building through the windows and the Space Heating Load of a building respectively.

Chapter 4

BUILDING ARCHITECTURE

Optimum level of building insulation not only helps lower monthly energy bills, but also adds to the overall comfort. Insulation helps maintain comfort temperature by reducing leakages. With the advent of green technologies and practices, the potential to save energy by design today can be as high as 40-50 %. Insulation in buildings is assuming tremendous importance and has a potential to reduce energy consumption .Buildings without insulation and air-tight envelope can result in major energy wastage[*Building Insulation Bulletin –Indian Green Building Council,April 2008*].

Benefits of Insulation

- Provides thermal as well as acoustical insulation.
- Resistant to moisture.
- Resistant to air infiltration.

Applications of Insulation materials

- Exterior walls.
- Interior walls
- Over the deck (roof)

4.1 Properties to consider in the selection of Insulation materials

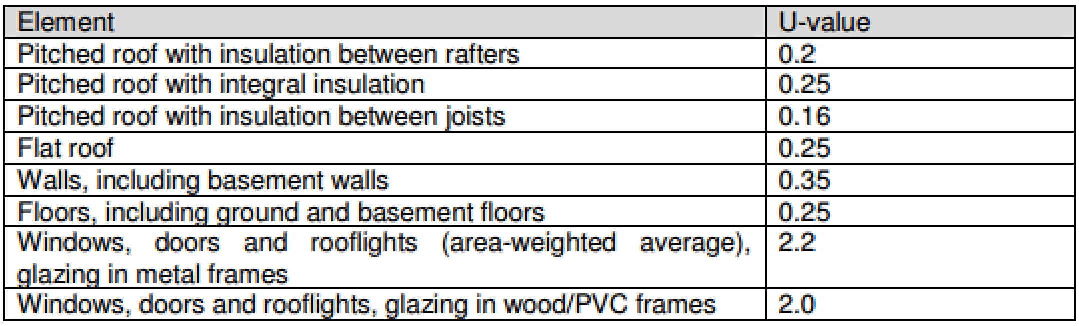
R-value: Insulation is rated in terms of thermal resistance, called R-value, which indicates the resistance to heat flow. The higher the R-value, the greater the insulating effectiveness. The R-value of thermal insulation depends on the type of material, its thickness and its density. R-value is the reciprocal of the time rate of heat flow through a unit area induced by a unit temperature difference between two defined surfaces of material or construction under steady-state conditions. R-value is expressed in m^2 K/W

U-factor (thermal transmittance) : The heat transmission in unit time through unit area of a material or construction and the boundary air films, induced by unit temperature difference between the environments 2 on each side. U-value is expressed in W/m^2K. The relationship between U-factor and R-value is not always exactly the inverse and therefore R-value cannot be precisely extrapolated for a material of different thickness. However, assuming an inverse relationship may be adequate

Fabric Heat Loss : Building regulations deal with design standards for fabric heat loss, and have historically set minimum insulation levels in terms of elemental U values. Each element of the building envelope (roof, wall, floor, window, door) is assigned a maximum heat loss rate. The unit of measurement, Watts per square metre Kelvin (W/m^{2}K), is an expression of how quickly energy passes through a square metre of the element for a given temperature drop between inside and out. The aim is to slow down the rate of heat loss, which means a lower U value.

Table 4-1: Maximum U Values(W/m^{2}K)

Source : The Building Regulations 2000 (England and Wales)

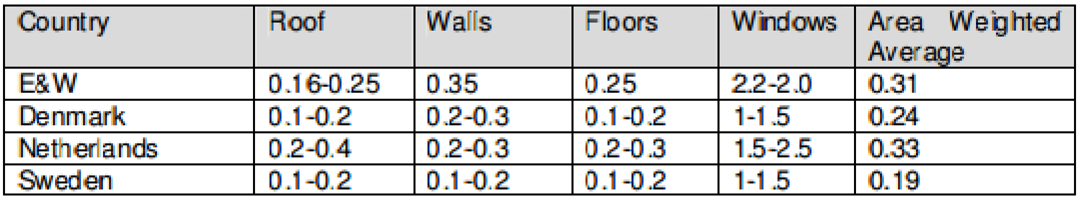


Element	U-value
Pitched roof with insulation between rafters	0.2
Pitched roof with integral insulation	0.25
Pitched roof with insulation between joists	0.16
Flat roof	0.25
Walls, including basement walls	0.35
Floors, including ground and basement floors	0.25
Windows, doors and rooflights (area-weighted average), glazing in metal frames	2.2
Windows, doors and rooflights, glazing in wood/PVC frames	2.0

4.2 Building Regulations and the EU

Table 4-2 compares Building Regulations in England and Wales, Denmark and The Netherlands. These countries are chosen because of the broad similarities in climate. Data on Sweden is included as it is presently the best EU standard. The standards required in Denmark are much higher than England and Wales and were also issued over 4 years before. As a result of these regulations a detached building built to the latest standards in England and Wales consumes nearly 20% more energy than an equivalent home in Denmark.

Table 4-2:The elemental U-value(W/m^{2}K) requirements for new build under four EU country's Regulations (EST, 2002)

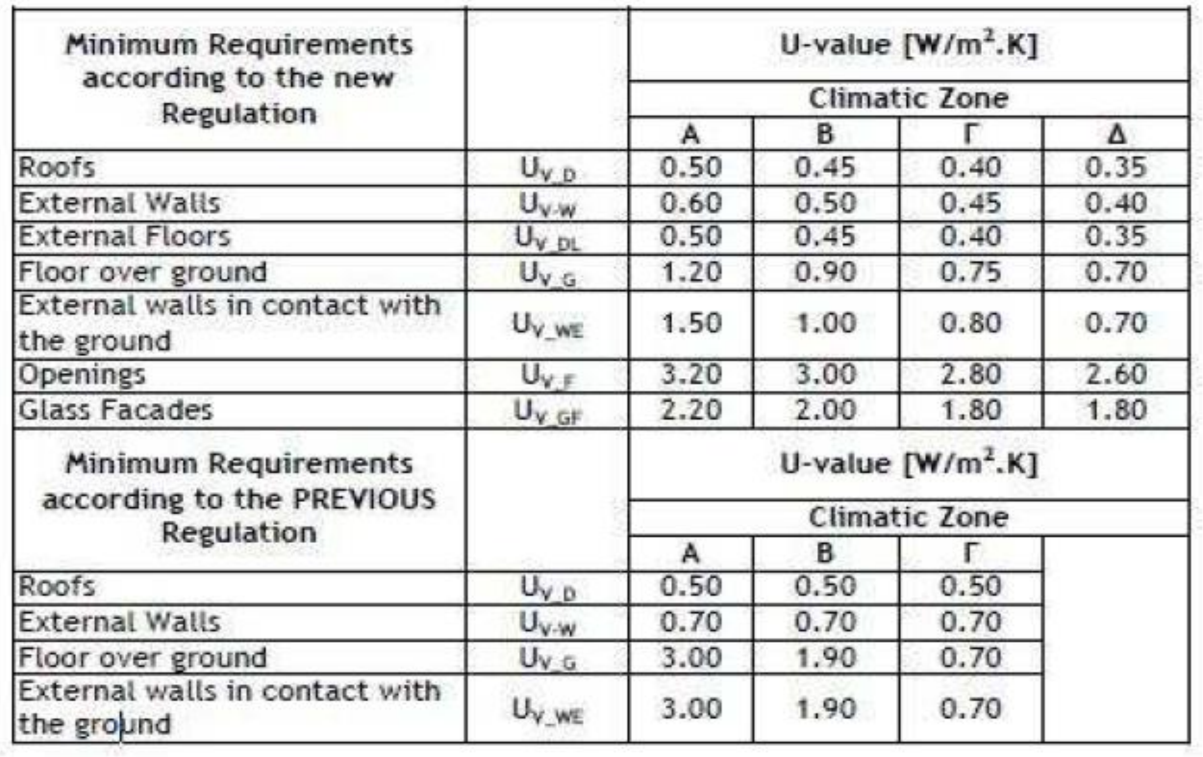


Country	Roof	Walls	Floors	Windows	Area Weighted Average
E&W	0.16-0.25	0.35	0.25	2.2-2.0	0.31
Denmark	0.1-0.2	0.2-0.3	0.1-0.2	1-1.5	0.24
Netherlands	0.2-0.4	0.2-0.3	0.2-0.3	1.5-2.5	0.33
Sweden	0.1-0.2	0.1-0.2	0.1-0.2	1-1.5	0.19

4.2.1 Building Regulation (Greece)

In Greece, the regulation of energy efficient buildings KENAK refers to the standard ISO 13790 as well as other international standards that define all the parameters related to the Greek requirements. Since the implementation of Energy Performance of Buildings Directive(EPBD), there were not any specific regulations defined in Greece regarding the energy performance and the evaluation of buildings. The only regulations related with the thermal performance of building were the national Thermal Insulation Regulation (TIR) introduced in 1981 and the Technical codes related with the installation of heating and cooling systems[22]. The thermal insulation regulations required to achieve low U values are given below. The smaller the U value is, less thermal loss exists and the better the insulation of the building is. The U value had to be lower than the value that the regulations indicated.

Table 4-3:Minimum U values(W/m^{2}K) according to the new and previous regulations[23]



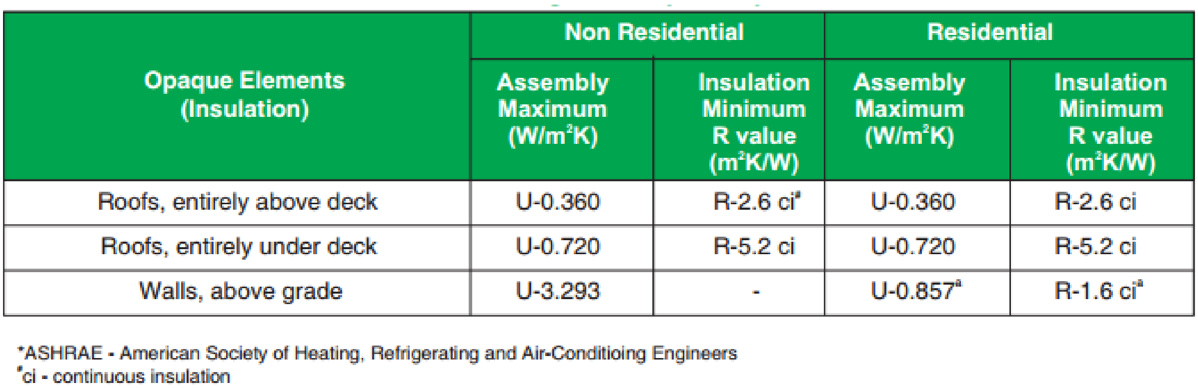
Minimum Requirements according to the new Regulation		U-value [W/m^2.K]			
		Climatic Zone			
		A	B	Γ	Δ
Roofs	U_{V_D}	0.50	0.45	0.40	0.35
External Walls	$U_{V\text{-}W}$	0.60	0.50	0.45	0.40
External Floors	U_{V_DL}	0.50	0.45	0.40	0.35
Floor over ground	U_{V_G}	1.20	0.90	0.75	0.70
External walls in contact with the ground	U_{V_WE}	1.50	1.00	0.80	0.70
Openings	U_{V_F}	3.20	3.00	2.80	2.60
Glass Facades	U_{V_GF}	2.20	2.00	1.80	1.80
Minimum Requirements according to the PREVIOUS Regulation		U-value [W/m^2.K]			
		Climatic Zone			
		A	B	Γ	
Roofs	U_{V_D}	0.50	0.50	0.50	
External Walls	$U_{V\text{-}W}$	0.70	0.70	0.70	
Floor over ground	U_{V_G}	3.00	1.90	0.70	
External walls in contact with the ground	U_{V_WE}	3.00	1.90	0.70	

4.2.2 Building Regulation(India)

Table 4-4 shows the Building envelope requirements for Non-residential and Residential as per ASHRAE.

Table 4-4:ASHRAE* Building Envelope Requirements

(Source :Building Insulation,Indian Green Building Council)



Opaque Elements (Insulation)	Non Residential		Residential	
	Assembly Maximum (W/m²K)	Insulation Minimum R value (m²K/W)	Assembly Maximum (W/m²K)	Insulation Minimum R value (m²K/W)
Roofs, entirely above deck	U-0.360	R-2.6 ci[a]	U-0.360	R-2.6 ci
Roofs, entirely under deck	U-0.720	R-5.2 ci	U-0.720	R-5.2 ci
Walls, above grade	U-3.293	-	U-0.857[a]	R-1.6 ci[a]

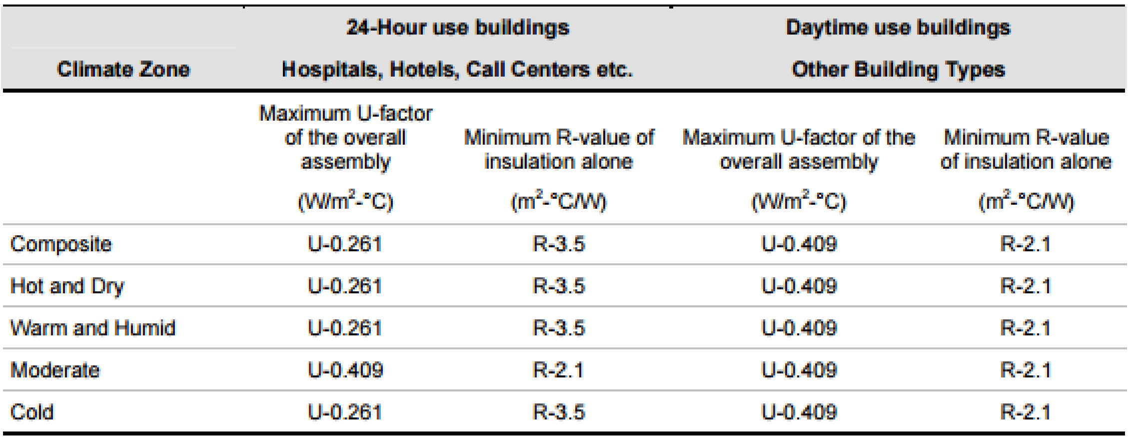
*ASHRAE - American Society of Heating, Refrigerating and Air-Conditioing Engineers

[a] ci - continuous insulation

Tables 4-5 and 4-6 show the U-factor and Insulation R-value requirements for each climatic zones in India.

Table 4-5:Roof assembly U-factor and Insulation R-value Requirements

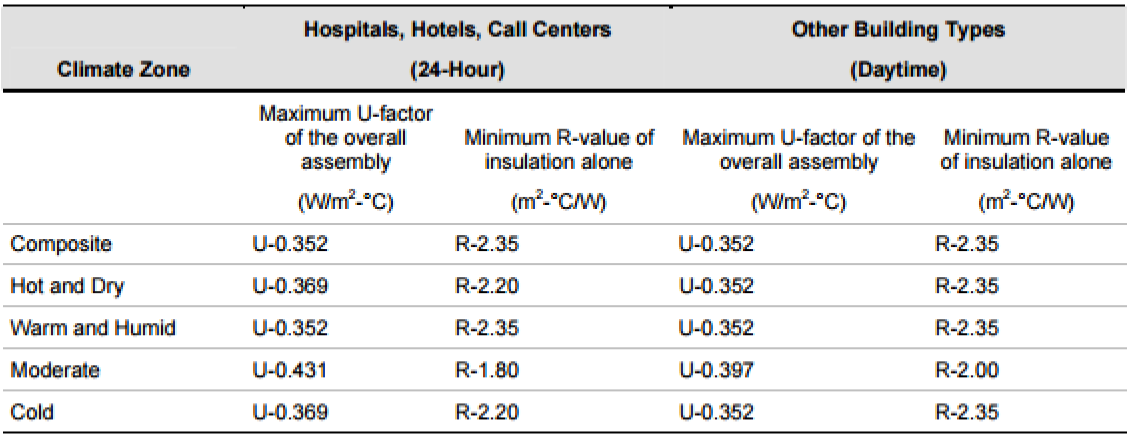
(Source :Energy Conservation Building Code,2006)



Climate Zone	24-Hour use buildings Hospitals, Hotels, Call Centers etc.		Daytime use buildings Other Building Types	
	Maximum U-factor of the overall assembly (W/m²-°C)	Minimum R-value of insulation alone (m²-°C/W)	Maximum U-factor of the overall assembly (W/m²-°C)	Minimum R-value of insulation alone (m²-°C/W)
Composite	U-0.261	R-3.5	U-0.409	R-2.1
Hot and Dry	U-0.261	R-3.5	U-0.409	R-2.1
Warm and Humid	U-0.261	R-3.5	U-0.409	R-2.1
Moderate	U-0.409	R-2.1	U-0.409	R-2.1
Cold	U-0.261	R-3.5	U-0.409	R-2.1

Table 4-6:Opaque Wall assembly U-factor and Insulation R-value Requirements

(Source :Energy Conservation Building Code,2006)



Climate Zone	Hospitals, Hotels, Call Centers (24-Hour)		Other Building Types (Daytime)	
	Maximum U-factor of the overall assembly (W/m²-°C)	Minimum R-value of insulation alone (m²-°C/W)	Maximum U-factor of the overall assembly (W/m²-°C)	Minimum R-value of insulation alone (m²-°C/W)
Composite	U-0.352	R-2.35	U-0.352	R-2.35
Hot and Dry	U-0.369	R-2.20	U-0.352	R-2.35
Warm and Humid	U-0.352	R-2.35	U-0.352	R-2.35
Moderate	U-0.431	R-1.80	U-0.397	R-2.00
Cold	U-0.369	R-2.20	U-0.352	R-2.35

Chapter 5

CALCULATION OF BUILDING LOADS(THERMAL AND ELECTRIC)

5.1 Determination of Thermal Heat losses Coefficient $(UA)_b$ of a Building

The following example outlines the process for calculating the Heat Losses coefficient ,U of the Building (*Douglas J.Harris,2015*).The U-value is a measure of the heat transfer through a building element such as a wall and is measured in W/m^{2}K. It can be considered to comprise three main thermal resistances: the inner surface resistance,the resistance to conduction of the wall itself, and the outer surface resistance. The wall resistance is the sum of the resistances of the individual layers; the resistance of each layer is simply the thickness t_n divided by its thermal conductivity k_n.

$$U = \frac{1}{R_t} \tag{5-1}$$

$$R_t = R_{si} + R_w + R_{so}$$

$$R_w = R_1 + R_2 + \dots$$

$$R_n = \frac{t_n}{k_n} \tag{5-2}$$

For a single-leaf brick wall in a ‘normal’ location (neither highly sheltered nor highly exposed) the following values are used:

Without insulation :

t_w = 105 mm, k_w = 0.44

R_w = 0.105/0.44 = 0.238 m^{2}K/W

R_{si} = 0.123 m^{2}K/W

R_{so} = 0.055 m^{2}K/W

R_t = 0.123 + 0.238 + 0.055

= 0.417 m^{2}K/W

U = 2.4W/m^{2}K.

With insulation :

Adding 50 mm of insulation with thermal conductivity k = 0.035 W/mK gives:

R_{ins} = 0.05/0.035 = 1.428

R_t = 0.123 + 0.238 + 1.428 + 0.055 = 1.845

U = 0.54 W/m^{2}K

Adding a further 50 mm of insulation gives;

R_{ins} = 0.1/0.035 = 2.856

R_t = 0.123 + 0.238 + 2.856 + 0.055 = 3.273

U = 0.305 W/m^{2}K

It is clear from the example that the benefit of adding insulation is subject to a law of diminishing returns. The first 50 mm of insulation reduces the U-value by 1.86, while the second 50 mm reduces it by only 0.23.Fig.5-1 shows the effect on the U-value of adding different thicknesses of insulation to a plain brick wall.

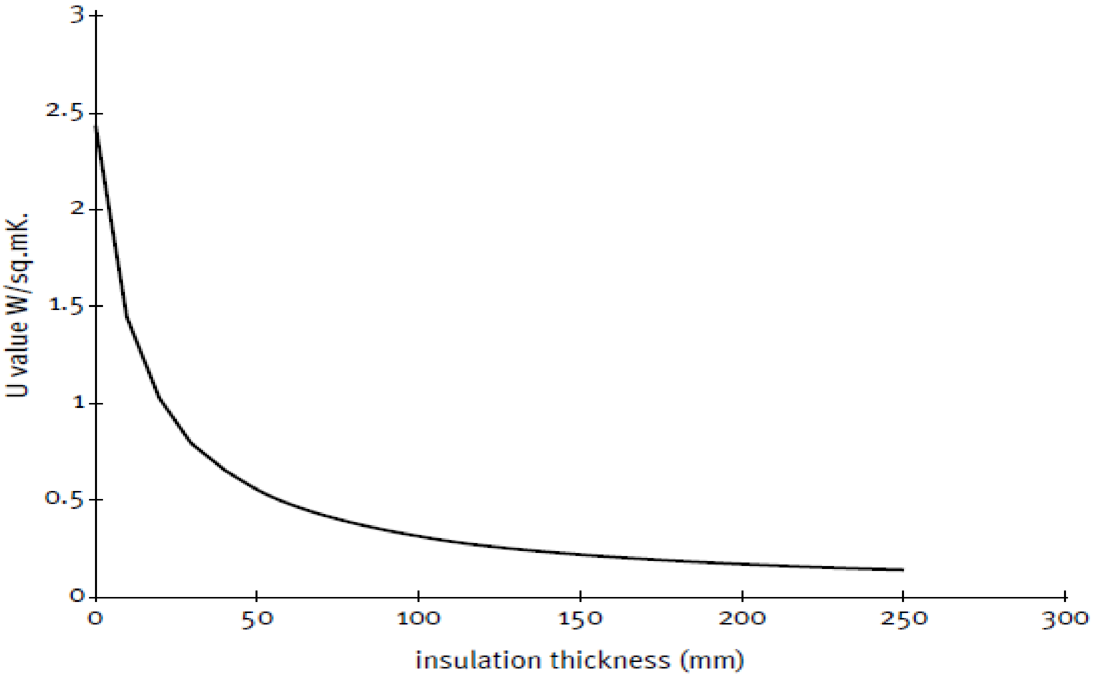


Figure 5-1: Effect of insulation thickness on U-value

(Source **:** A guide to energy management in Buildings)

The Overall U-Value of the building is given by the equation :

$$U = \frac{1}{R} = \left(\frac{1}{h_i} + \Sigma\frac{\Delta x}{k} + \frac{1}{h_o}\right)^{-1} \qquad 5\text{-}3$$

Where 1/h_i and 1/h_o represent the thermal resistances inside and outside the building.

$$h_i = h_{c,i} + h_{r,i} \qquad 5\text{-}4$$

Where $h_{c,i}$ and $h_{r,i}$ are the convective and the radiative components of the resistances respectively.

The U-Value and the thermal resistance,R of the individual components of the building per unit area are given by :

$$\frac{1}{u_{wall}} = R_{wall} = \frac{1}{h_i A_{wall}} + \Sigma\left(\frac{\Delta x}{kA_{wall}}\right) + \frac{1}{h_o A_{wall}} \qquad 5\text{-}5$$

$$\frac{1}{u_{windows}} = R_{windows} = \frac{1}{h_i A_{windows}} + \Sigma\left(\frac{\Delta x}{kA_{windows}}\right) + \frac{1}{h_o A_{windows}} \qquad 5\text{-}6$$

$$\frac{1}{u_{door}} = R_{door} = \frac{1}{h_i A_{door}} + \Sigma\left(\frac{\Delta x}{kA_{door}}\right) + \frac{1}{h_o A_{door}} \qquad 5\text{-}7$$

Therefore,

$$(UA)_b = \Sigma\left(\frac{1}{h_i} + \Sigma\frac{\Delta x}{k} + \frac{1}{h_o}\right)^{-1} A \qquad 5\text{-}8$$

For the sake of calculation,in all the cities,$h_{c,i}$ =5 W/m^{2}K ,$h_{r,i}$ = 5Wm^{2}K and h_o = 20W/m^{2}K (for London),h_o = 15W/m^{2}K (for Patras) and h_o = 10 W/m^{2}K(for Chennai).The value of h_o which is dependent on the wind speed is choosen based on the wind speed in each city .

5.1.1 Calculation of $(UA)_b$ of the Building

A single storey building is considered in all 3 cities with the dimensions and building elements as given in Tables 5-1 & 5-2.

Table 5-1: Building Parameters

Parameter	Value
Length	15m
Width	10m
Height	3m
Roof	Plaster-Wood-Insulation -Roof Tile
Roof Inclination(London)	40°
Roof Inclination(Patras)	10°
Terrace Elements(Chennai)	Plaster – Brick – Concrete - Tiles

Note : For the same building in Chennai ,there is no roof but only terrace

Table 5-2:Building Elements

Façade Facing	Elements
South	2 Vertical sealed double glazed window with distance between glasses 20mm (2m X 1.5m) ,Wooden door (25mm thickness,1m length and 1.5m Height,Wall comprising the layer : Plaster-Brick-Insulation-Brick-Plaster
North	2 Vertical sealed double glazed window with distance between glasses 20mm (2m X 1.5m), Wall comprising the layer : Plaster-Brick-Insulation-Brick-Plaster
West	1 Vertical sealed double glazed window with distance between glasses 20mm (2m X 1.5m), Wall comprising the layer : Plaster-Brick-Insulation-Brick-Plaster
East	1 Vertical sealed double glazed window with distance between glasses 20mm (2m X 1.5m),Wall comprising the layer : Plaster-Brick-Insulation-Brick-Plaster

Table 5-3: Building Elements Thickness and Thermal Conductivity

(Source :ASHRAE)

Building Element	Element Layers	Thickness,t (m)	Thermal Conductivity,k (W/m.k)	Thermal Resistance,R(m^2K/W)= t/k
Roof	Plaster Board	0.013	0.581	0.022
	Wood	0.020	0.465	0.043
	Polystyrene (London/Patras/ Chennai)	0.067,0.066,0.076	0.034	1.976,1.947,2.235
	Roof Tile	0.030	0.233	0.129
Total resistance of roof(conduction part)				2.547

Wall	Plaster	0.020	0.727	0.028
	Brick	0.100	1.333	0.075
	Insulation (London/Patras/ Chennai)	0.104,0.075,0.055	0.043	2.419,1.744,1.279
	Brick	0.100	1.333	0.075
	Plaster	0.020	0.727	0.028
Total resistance of Wall(conduction part)				1.019
Door	Wood	0.025	0.121	0.207
Terrace	Plaster	0.013	0.581	0.022
	Brick	0.1	1.333	0.075
	Concrete	0.1	0.813	0.123
	Tile	0.030	0.233	0.129
Total resistance of Terrace(conduction part)				0.349

As observed in Table 5-3,only the thickness of polystyrene in the Roof and the thickness of insulation in the wall changes between the three cities.The thermal Resistance, R pertaining to the conduction part($\Delta x/k$) is calculated for each of the components of the building in Table 5-3 .

Table 5-4:$(UA)_b$ of the building (London)

h_i(W/m^{2}K)	10	h_o(W /m^{2}K)	20							
Facade Facing	South			North		West		East		Roof
Description	Window (2 no.s)	Door (1 no.)	Wall	Window (2 no.s)	Wall	Window (1 no.)	Wall	Window (1 no.)	Wall	
Length,m	2	1		2		2		2		15
Height,m	1.5	1.5		1.5		1.5		1.5		13.054
Area,m^2	6	1.5	37.5	6	39	6	24	6	24	195.811
Thermal Resistance, R(m^{2}K/W)	0.081	0.238	0.074	0.081	0.071	0.081	0.116	0.081	0.116	0.012
Total Resistance of the building,R_b (m^{2}K/W)									0.948	
U-Value of the Building($1/R_b$),(W/m^{2}K)									1.055	
$(UA)_b$ of the building (W/K)									364.765	

In Table 5-4,the wall area is calculated by subtracting the area of the windows (and door for south façade)from the total area of each façade .The total area of the facades facing North and South are (15mX3m) = 45 m^2 and the total area of the facades facing East and west are (10mX3m) = 30m^2.The thermal resistance,R of each component of the building on all facades is determined by equations (5-5) to (5-7).The total thermal resistance of the building is the sum of all individual resistance of all components on all facades. The U-Value of the building is then the reciprocal of R as given by equation (5-3).Finally,the total Heat Loss coefficient of the building, $(UA)_b$ is calculated by multiplying the U-value of the building with the total surface area of the building as in equation (5-8).

The above calculation procedure is repeated for the building in Patras,Greece by changing the Roof inclination to 10^o and the $(UA)_b$ is calculated as shown in Table 5-5 .

Table 5-5: $(UA)_b$ of the building(Patras)

h_i(W/m^{2}K)	10	h_o(W/m^{2}K)	15							
Facade Facing	South			North		West		East		Roof
Description	Window (2 no.s)	Door (1 no.)	Wall	Window (2 no.s)	Wall	Window (1 no.)	Wall	Window (1 no.)	Wall	
Length,m	2	1		2		2		2		15
Height,m	1.5	1.5		1.5		1.5		1.5		10.154
Area,m^2	6	1.5	37.5	6	39	6	24	6	24	152.314
Thermal Resistance, R(m^{2}K/W)	0.083	0.249	0.056	0.083	0.054	0.083	0.088	0.083	0.088	0.015
Total Resistance of the building,R_b (m^{2}K/W)									0.884	
U-Value of the Building(1/R_b),(W/m^{2}K)									1.131	
$(UA)_b$ of the building (W/K)									341.852	

For the building in Chennai,the only change from that of the buildings in London and Patras is that the roof is replaced by a terrace with the procedure for calculating $(UA)_b$ remaining the same .The $(UA)_b$ for the building in Chennai is shown in Table 5-6.

Table 5-6:(UA)$_b$ of the building (Chennai)

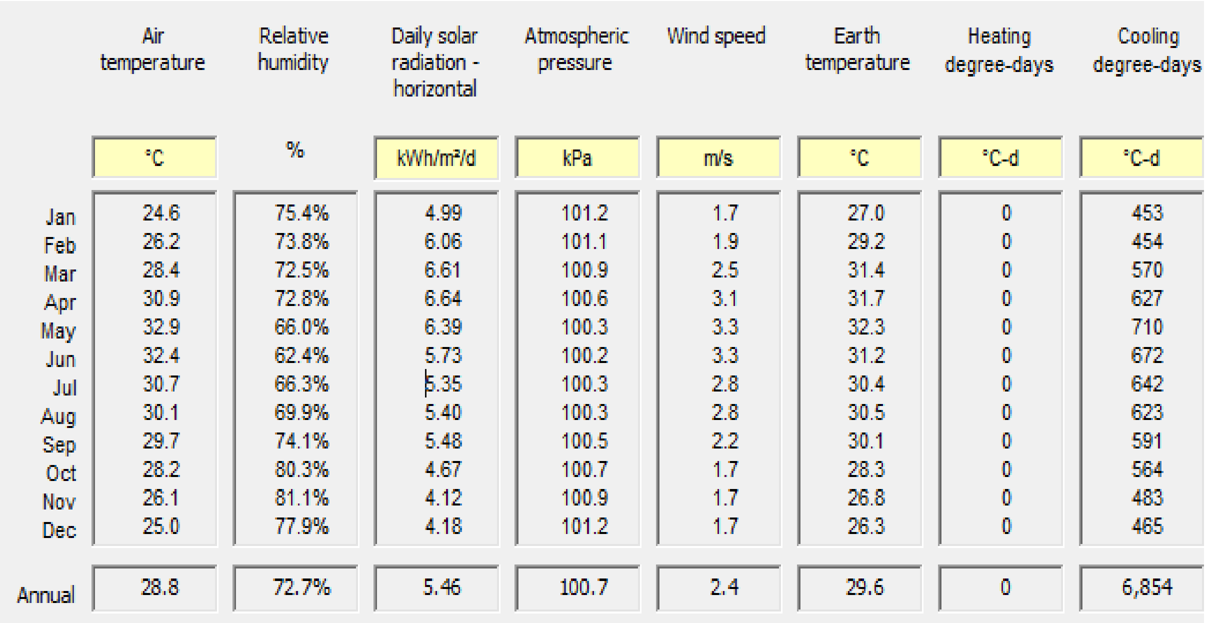
h_i(W/m^{2}K)	10	h_o(W/m^{2}K)	10							
Facade Facing	South			North		West		East		Terrace
Description	Window (2 no.s)	Door (1 no.)	Wall	Window (2 no.s)	Wall	Window (1 no.)	Wall	Window (1 no.)	Wall	
Length,m	2	1		2		2		2		15
Height,m	1.5	1.5		1.5		1.5		1.5		10.000
Area,m^2	6	1.5	37.5	6	39	6	24	6	24	150.000
Thermal Resistance, R(m^{2}K/W)	0.089	0.271	0.045	0.089	0.043	0.089	0.070	0.089	0.070	0.018
Total Resistance of the building,R_b (m^{2}K/W)									0.873	
U-Value of the Building(1/R_b),(W/m^{2}K)									1.146	
(UA)$_b$ of the building (W/K)									343.802	

5.2 Heating and Cooling Degree Days for 3 cities

From Table 5-7,it can be noticed that the average ambient temperatures in all the months is greater than the reference temperature selected to exist in the building i.e.,22°C.Hence the building in Chennai will have Cooling Loads prominently and no Heating Loads .

Table 5-7: Heating and Cooling Degree Days(Chennai)

(Source :RetScreen)

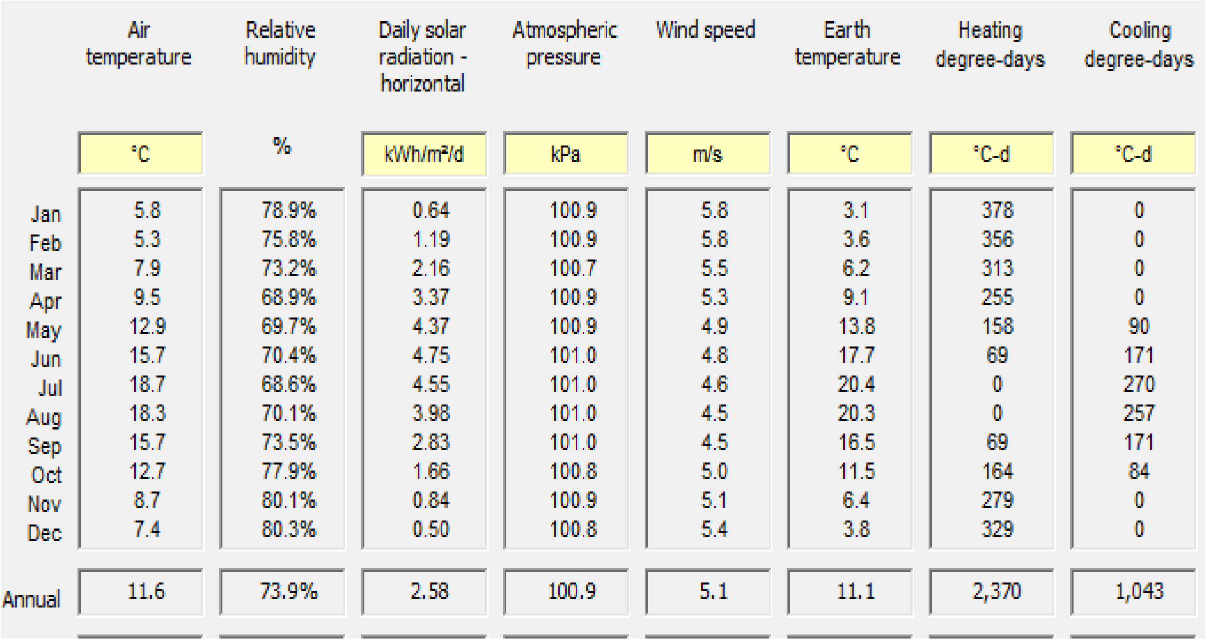


	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
Jan	24.6	75.4%	4.99	101.2	1.7	27.0	0	453
Feb	26.2	73.8%	6.06	101.1	1.9	29.2	0	454
Mar	28.4	72.5%	6.61	100.9	2.5	31.4	0	570
Apr	30.9	72.8%	6.64	100.6	3.1	31.7	0	627
May	32.9	66.0%	6.39	100.3	3.3	32.3	0	710
Jun	32.4	62.4%	5.73	100.2	3.3	31.2	0	672
Jul	30.7	66.3%	5.35	100.3	2.8	30.4	0	642
Aug	30.1	69.9%	5.40	100.3	2.8	30.5	0	623
Sep	29.7	74.1%	5.48	100.5	2.2	30.1	0	591
Oct	28.2	80.3%	4.67	100.7	1.7	28.3	0	564
Nov	26.1	81.1%	4.12	100.9	1.7	26.8	0	483
Dec	25.0	77.9%	4.18	101.2	1.7	26.3	0	465
Annual	28.8	72.7%	5.46	100.7	2.4	29.6	0	6,854

Table 5-7 is presented here to suggest that further in the chapter,only the cooling loads of the the building in Chennai will be calculated as there are no Heating Loads .

Table 5-8: Heating /Cooling Degree Days London

(Source :RETSCREEN)

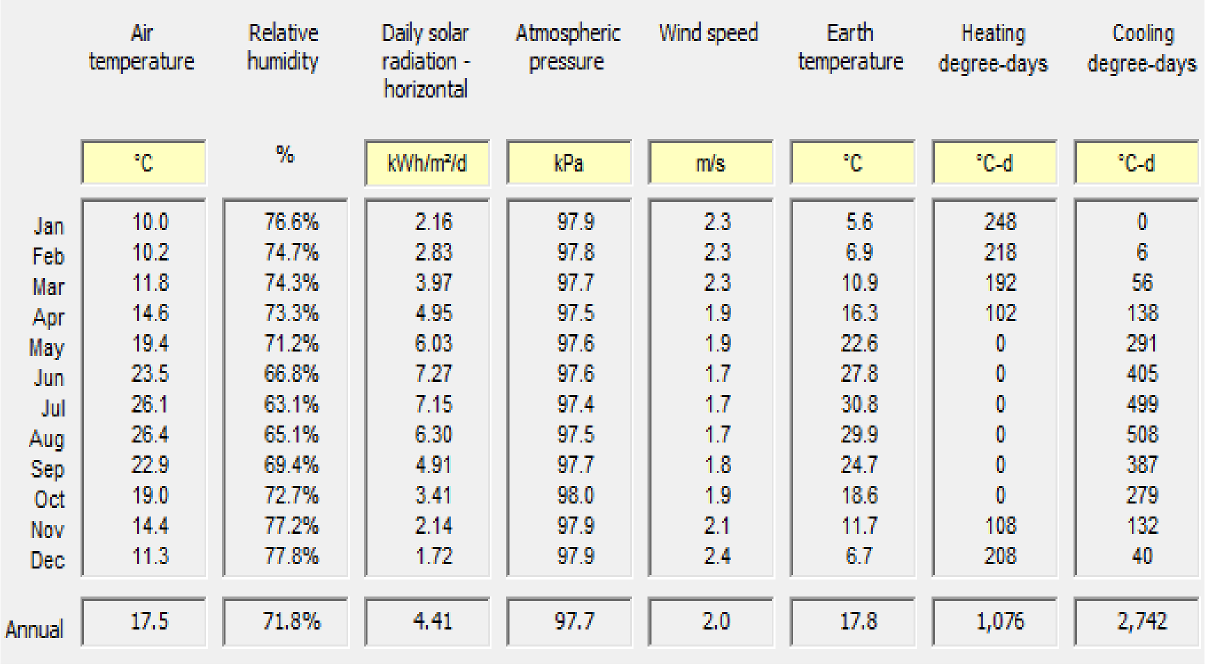


	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
Jan	5.8	78.9%	0.64	100.9	5.8	3.1	378	0
Feb	5.3	75.8%	1.19	100.9	5.8	3.6	356	0
Mar	7.9	73.2%	2.16	100.7	5.5	6.2	313	0
Apr	9.5	68.9%	3.37	100.9	5.3	9.1	255	0
May	12.9	69.7%	4.37	100.9	4.9	13.8	158	90
Jun	15.7	70.4%	4.75	101.0	4.8	17.7	69	171
Jul	18.7	68.6%	4.55	101.0	4.6	20.4	0	270
Aug	18.3	70.1%	3.98	101.0	4.5	20.3	0	257
Sep	15.7	73.5%	2.83	101.0	4.5	16.5	69	171
Oct	12.7	77.9%	1.66	100.8	5.0	11.5	164	84
Nov	8.7	80.1%	0.84	100.9	5.1	6.4	279	0
Dec	7.4	80.3%	0.50	100.8	5.4	3.8	329	0
Annual	11.6	73.9%	2.58	100.9	5.1	11.1	2,370	1,043

Tables 5-8 and 5-9 present the Heating and Cooling Degree days for London and Paptras respectively .It can be seen that the annual Heating Degree-days and the annual Cooling Degree-days for the building located in London is 2,370°C-d and 1,043 °C-d respectively.

Table 5-9:Heating /Cooling Degree Days Patras

(Source :RETSCREEN)



	Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
Jan	10.0	76.6%	2.16	97.9	2.3	5.6	248	0
Feb	10.2	74.7%	2.83	97.8	2.3	6.9	218	6
Mar	11.8	74.3%	3.97	97.7	2.3	10.9	192	56
Apr	14.6	73.3%	4.95	97.5	1.9	16.3	102	138
May	19.4	71.2%	6.03	97.6	1.9	22.6	0	291
Jun	23.5	66.8%	7.27	97.6	1.7	27.8	0	405
Jul	26.1	63.1%	7.15	97.4	1.7	30.8	0	499
Aug	26.4	65.1%	6.30	97.5	1.7	29.9	0	508
Sep	22.9	69.4%	4.91	97.7	1.8	24.7	0	387
Oct	19.0	72.7%	3.41	98.0	1.9	18.6	0	279
Nov	14.4	77.2%	2.14	97.9	2.1	11.7	108	132
Dec	11.3	77.8%	1.72	97.9	2.4	6.7	208	40
Annual	17.5	71.8%	4.41	97.7	2.0	17.8	1,076	2,742

The annual Heating Degree-days and the annual Cooling Degree-days for the building located in Patras is 1,076°C-d and 2,742°C-d respectively.However,it is to be noted that the above Tables have shown the Heating Degree days calculated for a base temperature of 18°C and the cooling Degree days for a base temperature of 10°C whereas the reference temperature selected inside the building is 22°C.Hence,while calculating the thermal loads(Heating and Cooling) the degree days from the above tables are converted to the reference temperature of 22°C by means of suitable equations which will be enlisted further in this chapter.

5.3 Calculation of Solar Gain for the Windows in London,January

Before introducing the concept of renewables inside the building to satisfy the Load demand,it is of utmost importance to minimize the energy demand inside the building by means of passive solar techniques and factoring the solar gain inside the building which will reduce the building Heating Loads .From Table I-B in Appendix I, the global solar radiation intensity for each hour is calculated and tabulated as follows :

Table 5-10: Solar Radiation Intensity, London on representative day for January

Time Interval	Hourly Global Solar Radiation Intensity on the horizontal(W/m^2)
8:00AM-9:00AM	35.75
9:00AM-10:00AM	85.75
10:00AM-11:00AM	119.5
11:00AM-12:00PM	137
12:00PM-1:00PM	137
1:00PM-2:00PM	119.5
2:00PM-3:00PM	85.75
3:00PM-4:00PM	42

The declination angle δ is calculated by means of the following equation :

$$\delta = 23.45 * \mathrm{Sin}\left(360 * \frac{284 + n}{365}\right) \qquad 5\text{-}9$$

Region -London									
Located in : UK									
Month Considered for the Analysis : January									
Latitude,φ		Longitude		Representative Day,n	Declination Angle,δ		Tanφ	Tanδ
Degrees	Radians	Degrees	Radians		Degrees	Radians	1.26	-0.38
51.51	0.90	0.13	0.00	17	-20.92	-0.37		

The Hourly Clearness index value K_T is calculated by :

$$K_T = \frac{I}{I_{ext}} \qquad 5\text{-}10$$

Where I is the hourly Global Solar Radiation Intensity,I_{ext} is the intensity of the solar radiation which reaches the outer space of the earth’s atmosphere given by

$$\begin{aligned} I_{ext} = \left(12 * \frac{3600}{\pi}\right).\, G_{sc}(1 + 0.033 \\ * Cos(\frac{360n}{365})[\big(Cos(\varphi).\,Cos(\delta).\,(Sin\omega_2 - Sin\omega_1)\big) \\ + 2\pi(\omega_2 - \omega_1).\,Sin(\varphi).\frac{Sin(\delta)}{360}) \end{aligned} \qquad 5\text{-}11$$

I_{sc} is the solar constant and is equal to 1353 W/m^2

ω is the hour angle

The fraction of diffuse based on the value of K_T is taken from Table 5-11 .

Table 5-11:Fraction of Diffuse given by Orgill and Hollands Model

Fraction of Diffuse	Value	Range
I_d/I	$1.0-0.249K_T$	$K_T < 0.35$
	$1.557-1.84K_T$	$0.35 \leq K_T < 0.75$
	0.177	$K_T \geq 0.75$

The Hourly Beam radiation is determined by the following equation.

$$I_b = I - I_d \qquad 5\text{-}12$$

Where ,

I_b is the Beam Radiation intensity in W/m^2

I is the Global Solar Radiation intensity in W/m^2

I_d is the Diffuse Radiation intensity in W/m^2

The different parameters calculated by using the equations (5-10) to (5-12) are tabulated in Table 5-12 :

Table 5-12: Hourly Beam and Diffuse Radiation

Time Interval	ω_1	ω_2	Hourly Solar Radiation Intensity,I_h(W/m^2)on the representative day(n=17)	Intensity of Extra-Terrestrial Radiation,I_{ext}	Hourly Clearness Index,K_T	Percentage(%) of Diffuse(I_d/I)	Hourly Diffuse Radiation (W/m^2),I_d	Hourly Beam Radiation(W/m^2),I_b
8:00AM-9:00AM	-60	-45	35.75	266.20	0.134	0.967	34.55	1.20
9:00AM-10:00AM	-45	-30	85.75	415.77	0.206	0.949	81.35	4.40
10:00AM-11:00AM	-30	-15	119.5	521.53	0.229	0.943	112.68	6.82
11:00AM-12:00PM	-15	0	137	576.28	0.238	0.941	128.89	8.11
12:00PM-1:00PM	0	15	137	576.28	0.238	0.941	128.89	8.11
1:00PM-2:00PM	15	30	119.5	521.53	0.229	0.943	112.68	6.82
2:00PM-3:00PM	30	45	85.75	415.77	0.206	0.949	81.35	4.40
3:00PM-4:00PM	45	60	42	266.20	0.158	0.961	40.35	1.65
Total			**762.25**					

For obtaining the value of Transmittance **τ,** the glass window is assumed to have the following properties :

Table 5-13: Properties of Glass Windows

Thickness of Glass,L = 0.003m
Extinction Coefficient of Glass, $\lambda = 10m^{-1}$
Angle of incidence of the Solar Beam Angle of Refraction,$\theta_1 = 30^o$
Refractive Index of the Glass = 1.52

Angle of Refraction,θ_2 is determined using Snell's law which is given by :

$$Sin(\theta_1)/Sin(\theta_2) = n \quad 5\text{-}13$$

The coefficient of transmission τ_α is given by:

$$\tau_\alpha = \exp((-\lambda L/\mathrm{Cos}(\theta_2)) \qquad 5\text{-}14$$

The reflection coefficients for the two polarized components at the normal and parallel plane to the medium in which the beam travels is given by :

$$r_n = Sin^2(\theta_2 - \theta_1)/Sin^2(\theta_2 + \theta_1) \qquad 5\text{-}15$$

$$r_p = tan^2(\theta_2 - \theta_1)/tan^2(\theta_2 + \theta_1) \qquad 5\text{-}16$$

The transmission coefficient τ_r of the medium is given by :

$$\tau_r = \frac{1}{2} * [\frac{1-r_p}{1+r_p} + \frac{1-r_n}{1+r_n}] \qquad 5\text{-}17$$

The transmission coefficient of the Glass is given by :

$$\tau = \tau_\alpha . \tau_r \qquad 5\text{-}18$$

The above terms are calculated and tabulated as below :

Table 5-14: Transmission Coefficient of Glass

Angle of incidence of solar Beam,θ_1(degrees)	Refractive Index of Glass	Angle of Refraction,θ_2 (degrees)	Coefficient of Transmission,τ_α	r_n	r_p	Transmission Coefficient ,τ_r	Transmission Co-efficient,$\tau=\tau_\alpha*\tau_r$
30	1.52	19.2049	0.9687	0.0612	0.0271	0.9160	0.8873

The transmission coefficient of the Glass Windows is therefore 0.88 and the hourly Solar Gain is calculated as shown in Table 5-15 .

Table 5-15: Hourly Solar Gain for building in London,January

Angle of inclination ,β		Angle of orientation,γ		Transmission Coefficient,τ of Glass Windows	0.88	
Degrees	Radians	Degrees	Radians			
90	1.571	0	0.000	Absorptance,α	1	
Time Interval	Hour Angle,ω	COSθ	COSθ$_Z$	R$_b$ =(COSθ)/(COS θ$_Z$)	Hourly Solar Radiation Intensity on the Windows(W/m^2),I$_T$	Hourly Solar Gain(W/m^2),I$_T$τα
8:00AM-9:00AM	-45	0.739	0.132	5.613	23.99	21.11
9:00AM-10:00AM	-30	0.855	0.224	3.817	57.48	50.59
10:00AM-11:00AM	-15	0.928	0.282	3.290	78.77	69.32
11:00AM-12:00PM	0	0.953	0.302	3.157	90.05	79.24
12:00PM-1:00PM	15	0.928	0.282	3.290	91.13	80.19
1:00PM-2:00PM	30	0.855	0.224	3.817	82.37	72.48
2:00PM-3:00PM	45	0.739	0.132	5.613	65.39	57.55
3:00PM-4:00PM	60	0.588	0.011	52.159	106.24	93.49
Total					**595.42**	**523.97**

The angle of inclination in Table 5-15 refers to the inclination of the windows on the building.The parameters in the table are calculated by means of the equations (5-19) to (5-21):

θ is the angle of incidence of the Sun's Beam and

$$\begin{aligned} Cos\theta \; = \; & Sin\delta.Sin\varphi.Cos\beta - Sin\delta.Cos\varphi\,.Sin\beta.Cos\gamma \\ & + Cos\delta.Cos\varphi.Cos\beta.Cos\omega \\ & + Cos\delta\,.Sin\varphi.Sin\beta.Cos\gamma.Cos\omega + Cos\delta.Sin\beta.Sin\gamma.Sin\omega \end{aligned} \tag{5-19}$$

θ$_z$ is the Zenith Angle which is obtained when β =0 and γ =0

$$Cos\theta_z \; = \; Cos\delta.Cos\varphi.Cos\omega \; + \; Sin\varphi.Sin\delta \tag{5-20}$$

The hourly Solar Radiation Intensity values on the inclined plane(I$_T$) is given by

$$I_T \; = I_b.R_b \; + \; I_d.(1 + Cos\,\beta)/2 \; + \; r.(1 - Cos\,\beta)/2 \tag{5-21}$$

Where r is the reflectivity of the surface and is assumed to be negligible,

I$_b$ - Beam Radiation Intensity(W.m^2)

I$_d$ - Diffuse Radiation Intensity(W/m^2)

R_b – Conversion factor of the Beam component from horizontal to Inclined

The total area of the Windows on the South Wall of the Building is (2mX1.5m)*2 = 6 m^2

Hence the solar gain into the Building for the entire month of January = 523.97*31*6

= 97,458.42Wh

= 97.46kWh

The process for calculating Solar gain enlisted in this section is repeated for the other cities for all seasonal months and tabulated as shown in Table 5-16 .

Table 5-16: Solar gain (daily&monthly)for 3 cities

Solar Gain per	London				Patras				Chennai			
	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct
day(wh)	523.97	2173.23	1869.89	1172.77	1676.22	2488.49	1704.08	3020.92	3528.11	1132.35	942.23	2143.81
month(kWh)	97.46	391.18	347.80	218.14	311.78	447.93	316.96	561.89	656.23	203.82	175.25	398.75

5.4 Calculation of Space Heating, Cooling and other thermal Loads

In this section,the heating and the cooling Loads of the building are calculated.To calculate the same,the following are the parameters assumed to exist in the building.

Number of Occupants = 3
Mean Daily Water Consumption per occupant = 50 l
Mean Daily Operation of the hot water returns ,t = 16 h
Length of the Pipes ,l = 30m

Table 5-17: Mains Cold Water Temperature in 3 cities (For Patras taken from TECSOL and assumed values for other 2 cities)

City	Month	Temperature(°C)
Patras	Jan	12.8
	Apr	14.8
	Jul	24.4
	Oct	22.3

London	Jan	10.8
	Apr	12.8
	Jul	22.4
	Oct	20.3
Chennai	Jan	17.8
	Apr	19.8
	Jul	25.4
	Oct	23.0

The Load of Space Heating is given by

$$L_{sh} = 24\left(\frac{\mathbf{h}}{\mathbf{day}}\right) * (UA)_b(\mathbf{W\ per\ {}^oC}) * D(\mathbf{{}^oC.day}) \qquad 5\text{-}22$$

D is the degree-days of the sizing month

To convert the degree-days to a reference temperature T_{ref} other than 18°C

$$D = \left\{N.\Delta T_b + (0.744 + 0.00387D_\alpha - 0.5 * 10^{-6} * D_\alpha^2).N.\exp\left(-\left[\frac{\Delta T_b + 11.11}{9.02}\right]^2\right)\right\} \qquad 5\text{-}23$$

Where

$\Delta T_b = T_{ref} - T_a$

D_α is the annual degree-days at a temperature base of 18°C (which can be obtained from Tables 5-8 & 5-9 for London and Patras respectively).

$(UA)_b$ is the product of the overall mean heat transfer coefficient with the area of the external building surface.

The Load of Water Heating is given by :

$$L_w = N.V_w.\rho.C_p(T_w - T_m) \qquad 5\text{-}24$$

Where

N is the number of days of the month

V_w is the mean daily water consumption/occupant X the number of occupants

T_w is the Desired water temperature

T_m is the mains(Cold)Water Temperature

The Heat Losses in the Pipes is given by:

$$L_p = N.t.U.l \tag{5-25}$$

Where

t is the mean daily operation of the hot water returns (s)

l is the length of the pipes(m)

U is the mean heat losses coefficient in the pipes(W/m)

Total Load of Water Heating is

$$L_{h,w} = L_w + L_p \tag{5-26}$$

5.4.1 Space Heating & other Thermal Loads for London,Patras

To determine the load of space Heating,the Heating Degree days given for a base temperature of 18°C for cities London and Patras are taken from corresponding Tables 5-8 , 5-9 and converted to the reference temperature inside the building i.e.,22°C by using equation 5-23.Following this,the load of space Heating is calculated using equation 5-12 by substituting the converted Degree Days (D) and the $(UA)_b$ values for the respective city.The domestic Hot water load and the Heat losses in the pipes are calculated by equations (5-24) and (5-25) respectively. The calculated results are presented in Table 5-18.

Table 5-18: Thermal Loads for the Building in London and Patras

(Reference Temperature inside the building :22°C)

Load	London				Patras			
	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct
Heating (kWh)	4396.7	3284.9	1045.9	2535.4	3053.6	1837.2	0	858.317
Cooling (kWh)	-	-	184.80	-	0	294.68	927.91	94.05
Domestic Hot Water(kWh)	265.89	236.40	234.99	214.55	255.08	236.40	192.39	203.74
Heat Losses(kWh)	307.48	273.37	203.20	248.11	294.98	273.37	222.49	235.61

5.4.2 Space Heating Load calculation (Alternative approach by using hourly temperature data)

In section 5.4.1 , the space Heating loads were calculated by considering the monthly average ambient temperature value provided by RetScreen.In this section ,the values of the hourly temperature for a range of -3 to +3 days around the representative day of the month are obtained from MeteoNorm database. For each of these 7 days,the difference T_a and $T_{ref}(22^oC)$ $(T_{ref} - T_a)$ is calculated for each hour and added and the average of the 7 days is taken as the average Degree days for the respective month.This value when multiplied with the number of days of the month gives the total Heating Degree days for the corresponding month. If T_a is greater than T_{ref} ,it pertains to a cooling load .

To calculate the Space Heating load in January for London ,the hourly temperature data for ± 3 days representative days is obtained from Meteonorm as shown in Table 5-19.

Table 5-19:Hourly Temperature values ± 3 days representative day for London , January(n=17)

(Source : Meteonorm)

Hour	Ref Temp(°C)	Hourly Temperature (°C)						
		14th day	15th day	16th day	17th day	18th day	19th day	20th day
1	22	10.7	12.3	7.2	6.5	6	5.9	1.8
2	22	10.2	11.4	7	7.1	5.7	6.1	1.6
3	22	10.5	10.3	7.8	7.4	5	5.9	2.2
4	22	10.9	9.8	7.3	7.3	4.6	5.5	1.1
5	22	11.1	10.4	6.5	6.7	4.3	4.9	0.6
6	22	10.9	10.3	6.7	7.4	4.1	3.8	0.7
7	22	11.8	10.6	7.2	7.6	3.8	3.8	0.9
8	22	11.7	10.8	7.7	6.9	3.8	4	0.9
9	22	11.4	10.5	7.1	7.3	4.1	3.9	0.4
10	22	11.6	9.8	6.9	7	4.1	3.8	0.5
11	22	11.9	10.6	6.3	6.2	4.5	4.3	0.5
12	22	12.3	10.4	7	6	5.7	4.4	0.9
13	22	12.4	11.1	8	5.8	6.3	4.9	0.9
14	22	12.8	10.5	8	6.3	7.2	5.8	1.7
15	22	12.5	10.1	8.5	6.2	7.4	5.9	2.3
16	22	13.1	10.1	8.1	5.8	7	6	2.6
17	22	12.6	9.9	7.8	5.7	6.9	4.6	1.3
18	22	12.9	9.5	7.6	5.4	6.4	4.5	0.2

19	22	12.7	9.2	7.5	5.9	6.5	4.3	-0.2
20	22	12.8	8.4	7.1	5.3	7	3.3	0.1
21	22	12.1	7.9	6.7	6	6.9	2.7	-0.7
22	22	12.4	8	6.6	6.3	6	2.8	-1.2
23	22	12.1	7.4	6.8	5.8	5.9	2.8	-0.9
24	22	11.9	6.6	6.4	6.3	6.4	2.4	-1.2

For each of these days,the difference between the reference temperature,T_{ref}(^oC)and the ambient temperature,T_a(^oC) is calculated for each hour.Adding the 24 values obtained for each day gives the Heating Degree days(HDD) for the respective day.The average of the Heating Degree days is taken for the 7 days considered above.This gives the monthly average Heating Degree days. Multiplying this monthly average HDD value with the number of days in the month gives the Heating Degree days for the month.Finally,this total degree days for the month is multiplied with the $(UA)_b$ of the building of the respective city to obtain the Load of Space Heating as shown in Table 5-20.

Table 5-20:Space Heating Load considering hourly values of temperature London(January)

Hour	T_{ref} - T_a(^oC)[± 3 days around representative day]						
	14th day	15th day	16th day	17th day	18th day	19th day	20th day
1	11.3	9.7	14.8	15.5	16	16.1	20.2
2	11.8	10.6	15	14.9	16.3	15.9	20.4
3	11.5	11.7	14.2	14.6	17	16.1	19.8
4	11.1	12.2	14.7	14.7	17.4	16.5	20.9
5	10.9	11.6	15.5	15.3	17.7	17.1	21.4
6	11.1	11.7	15.3	14.6	17.9	18.2	21.3
7	10.2	11.4	14.8	14.4	18.2	18.2	21.1
8	10.3	11.2	14.3	15.1	18.2	18	21.1
9	10.6	11.5	14.9	14.7	17.9	18.1	21.6
10	10.4	12.2	15.1	15	17.9	18.2	21.5
11	10.1	11.4	15.7	15.8	17.5	17.7	21.5
12	9.7	11.6	15	16	16.3	17.6	21.1
13	9.6	10.9	14	16.2	15.7	17.1	21.1
14	9.2	11.5	14	15.7	14.8	16.2	20.3
15	9.5	11.9	13.5	15.8	14.6	16.1	19.7
16	8.9	11.9	13.9	16.2	15	16	19.4
17	9.4	12.1	14.2	16.3	15.1	17.4	20.7
18	9.1	12.5	14.4	16.6	15.6	17.5	21.8
19	9.3	12.8	14.5	16.1	15.5	17.7	22.2
20	9.2	13.6	14.9	16.7	15	18.7	21.9

21	9.9	14.1	15.3	16	15.1	19.3	22.7
22	9.6	14	15.4	15.7	16	19.2	23.2
23	9.9	14.6	15.2	16.2	16.1	19.2	22.9
24	10.1	15.4	15.6	15.7	15.6	19.6	23.2
Heating Degree Days(HDD)	242.7	292.1	354.2	373.8	392.4	421.7	511
Total Degree days for ± 3 days around representative day							2587.9
Average Degree days for January							369.7
Total Degree days for January,D							11460.7
Load of Space Heating for January,L_{sh}(kWh) [$(UA)_b$*D]							4180.485

5.4.3 Calculation of Cooling Loads for Chennai

The Cooling Loads are determined by use of equations enlisted in this section .

For unshaded or partially shaded windows, the load is

$$Q_{wi} = A_{wi}[F_{sh}\tau_{b,wi}I_{h,b}\left(\frac{Cosi}{Sin\alpha}\right) + \tau_{d,wi}I_{h,d} + \tau_{r,wi}I_r + U_{wi}(T_{out} - T_{in}) \qquad 5\text{-}27$$

For shaded windows the load (neglecting diffuse sky radiation) is

$$Q_{wi,sh} = A_{wi,sh}U_{wi}(T_{out} - T_{in}) \qquad 5\text{-}28$$

For unshaded walls the load is :

$$Q_{wa} = A_{wa}[\alpha_{s,wa}(I_r + I_{h,d} + I_{h,b}\left(\frac{Cosi}{Sin\alpha}\right) + U_{wa}(T_{out} - T_{in})] \qquad 5\text{-}29$$

For shaded walls the load (neglecting diffuse sky radiation) is

$$Q_{wa,sh} = A_{wa,sh}[U_{wa}(T_{out} - T_{in})] \qquad 5\text{-}30$$

For the roof,the load is

$$Q_{rf} = A_{rf}[\alpha_{s,rf}(I_{h,d} + I_{h,b}\left(\frac{cosi}{sin\alpha}\right) + U_{rf}(T_{out} - T_{in})] \qquad 5\text{-}31$$

For sensible-heat infiltration and exfiltration the load is

$$Q_i = m_a(h_{out} - h_{in}) \qquad 5\text{-}32$$

For moisture infiltration and exfiltration the load is

$$Q_w = m_a(W_{out} - W_{in})\lambda_w \qquad 5\text{-}33$$

Where

Q_{wi} is the heat flow through unshaded windows of area A_{wi} , W/hr

$Q_{wi,sh}$ is the heat flow through shaded windows of area $A_{wi,sh}$, W/hr

Q_{wa} is the heat flow through unshaded walls of area A_{wa} , W/hr

$Q_{wa,sh}$ is the heat flow through shaded walls of area $A_{wa,sh}$, W/hr

Q_{rf} is the heat flow through roof of area A_{rf} , W/hr

Q_i is the heat load resulting from infiltration and exfiltration , W/hr

Q_w is the latent heat load ,W/hr

$I_{h,b}$ is the beam component of insolation on horizontal surface,W/hr.m^2

$I_{h,d}$ is the diffuse component of insolation on horizontal surface, W/hr.m^2

I_r is the ground-reflected component of insolation, W/hr.m^2

W_{out},W_{in} are the outside and inside humidity ratios,kg$_m$ H_2O/kg$_m$ dry air

U_{wi} ,U_{wa},U_{rf} are the overall heat-transfer coefficients for windows,walls and roof including radiation, W/hr.m^2.^{o}C

m_a is the net infiltration and exfiltration of dry air,kg$_m$/hr

T_{out} is the outside dry-bulb temperature, ^{o}C

T_{in} is the indoor dry-bulb temperature, ^{o}C

F_{sh} is the shading factor (1.0 = unshaded,0.0 = fully shaded)

$\alpha_{s,wa}$ is the wall solar absorptance

$\alpha_{s,rf}$ is the roof solar absorptance

i is the solar-incidence angle on walls,windows and roof, deg

h_{out},h_{in} are the outside and inside air enthalpies

α is the solar-altitude angle,deg

λ_w is the latent heat of water vapor

$\tau_{b,wi}$ is the window transmittance for beam (direct) insolation

$\tau_{d,wi}$ is the window transmittance for diffuse insolation

$\tau_{r,wi}$ is the window transmittance for ground-reflected insolation

Table 5-21: Building Characteristics for Calculating Cooling Load

Terrace :	
Area	150
Walls(painted white)	
size,north and south,m	15x3(two)
size,east and west,m	10X3(two)
Area $A_{wa,}$north and south walls,m^2	45-A_{wi}
Area $A_{wa,}$north and south walls,m^2	30-A_{wi}
Absorptance $\alpha_{s,wa}$ of white paint	0.12
Windows	
size,north and south,m	2X1.5(two)
size,east and west,m	2X1.5(one)
Shading Factor F_{sh}	0.2
Insolation Transmittance	$\tau_{b,wi} = 0.60, \tau_{d,wi} = 0.81, \tau_{r,wi} = 0.60$
Location and Latitude,L	Chennai,India,13.08°N
Date	Apr-15
Time and local-Solar hour angle H_s	Noon;H_s=0
Solar declination δ_s,deg	$9^o41'$
Wall surface Tilt from horizontal β	90^o
Temperature,Outside and inside,°C	$T_{out} = 30.92; T_{in} = 22$
Insolation I,W/hr.m^2	$I_{h,b} = 568$; $I_{d,b} = 196.5$;$I_r = 229.35$
U factor for walls,windows and Terrace	$U_{wa} = 0.981$; $U_{wi} = 3$; $U_{terrace} = 0.349$
Infiltration,Exfiltration and Internal Loads	(Neglect)
Latent Heat Load Q_w ,Percent	30 percent of wall sensible Heat Load(assumed)

The Cooling Loads pertaining to the different segments of the building are computed by use of equations in this section and shown in Table 5-22.

Table 5-22: Cooling Load for April ,Chennai

Shaded Window Load		Shaded-Wall Load		Terrace Load		Latent Heat Load(30 percent of Sensible Wall Load)		Infiltration-Exfiltration Load	
$Q_{wi,sh}$	320.400	$Q_{wa,sh}$	811.974	$Q_{terrace}$	465.915	Q_{wa}	345.744	Q_i	0
Time	Hour Angle,H_s	$I_{h,b}$	$I_{h,d}$	I_r	Incidence angle for the south wall i ,Cosi	Solar Altitude α,Cosα	South-facing Window Load,Q_{wi}	South-facing Wall Load,Q_{wa}	Cooling Load hourly(W/hr)
6:30AM-7:30AM	-75	45.5	69	34.35	0.064	0.286	331.430	871.823	3147.285
7:30AM-8:30AM	-60	194.75	134.5	98.775	0.064	0.517	611.552	1544.820	4100.404
8:30AM-9:30AM	-45	372.5	173.75	163.875	0.064	0.717	875.409	2076.123	4895.564
9:30AM-10:30AM	-30	533.75	192	217.725	0.064	0.869	1084.247	2441.725	5470.004
10:30AM-11:30AM	-15	653.5	197.5	255.3	0.064	0.965	1225.624	2662.161	5831.817
11:30AM-12:30PM	0	717	198	274.5	0.064	0.998	1296.942	2766.747	6007.721
12:30PM-1:30PM	15	717	198	274.5	0.064	0.965	1298.063	2774.039	6016.135
1:30PM-2:30PM	30	653.5	197.5	255.3	0.064	0.869	1229.065	2684.531	5857.629
2:30PM-3:30PM	45	533.75	192	217.725	0.064	0.717	1090.271	2480.879	5515.182
3:30PM-4:30PM	60	372.5	173.75	163.875	0.064	0.517	884.611	2135.938	4964.581
4:30PM-5:30PM	75	194.75	134.5	98.775	0.064	0.286	625.601	1636.142	4205.775
5:30PM-6:30PM	90	45.5	69	34.35	0.064	0.037	380.669	1191.873	3516.574
Total Cooling Load(W) for the Representative day on April									59528.672
Total Cooling Load for the month of April(kWh)									***1785.860***

The procedure is repeated for the other seasonal months of Chennai and the cooling loads for all the seasonal months are tabulated in Table 5-23.

Table 5-23: Thermal Loads for the building in Chennai

(Reference Temperature inside the building :22°C)

Load	Chennai			
	Jan	Apr	Jul	Oct
Cooling (kWh)	1533.26	1785.86	1627.81	1511.85
Domestic Hot Water(kWh)	228.06	210.25	186.99	199.96
Heat Losses(kWh)	263.73	243.13	216.24	231.24

Now,the solar gain shown in Table 5-16 is to be subtracted from the Load of space Heating and to be added in case of cooling load.If both Heating and cooling Loads exist for a city in a particular month then depending on the load which is prominent ,the solar gain is subtracted or added.For instance,for London in July both Heating and cooling Loads are present as seen from Table 5-18.However,the Heating Load is much higher and hence,the solar gain is subtracted from the Heating Load.For Chennai ,equations presented in section 5.4.3 already factor in the solar radiation through the Windows and hence they are not separately added for

Chennai. Chapter 6 discusses in depth on how the prominent Load for the seasonal month (either Heating or Cooling)can be satisfied by Renewable Energy systems.

Table 5-24 presents the total thermal loads(calculated from first approach) for London and Patras after factoring the Solar Gain through the Windows .

Table 5-24: Total thermal Loads for London and Patras after factoring Solar Gain

(Reference Temperature inside the building :22^{o}C)

Load	London				Patras			
	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct
Heating (kWh)	4299.24	2893.72	698.10	2317.26	2741.82	1389.27	0.00	296.43
Cooling (kWh)	0	0	184.8	-	0	294.68	1244.87	94.05
Domestic Hot Water(kWh)	265.89	236.4	234.99	214.55	255.08	236.4	192.39	203.74
Heat Losses(kWh)	307.48	273.37	203.2	248.11	294.98	273.37	222.49	235.61
Total (Heating + Domestic Hot water +Heat Losses)	4872.61	3403.49	1136.29	2779.92	3291.88	1899.04	414.88	735.78

Fig.5-2 shows the different thermal loads across the 3 cities in the four seasonal months.

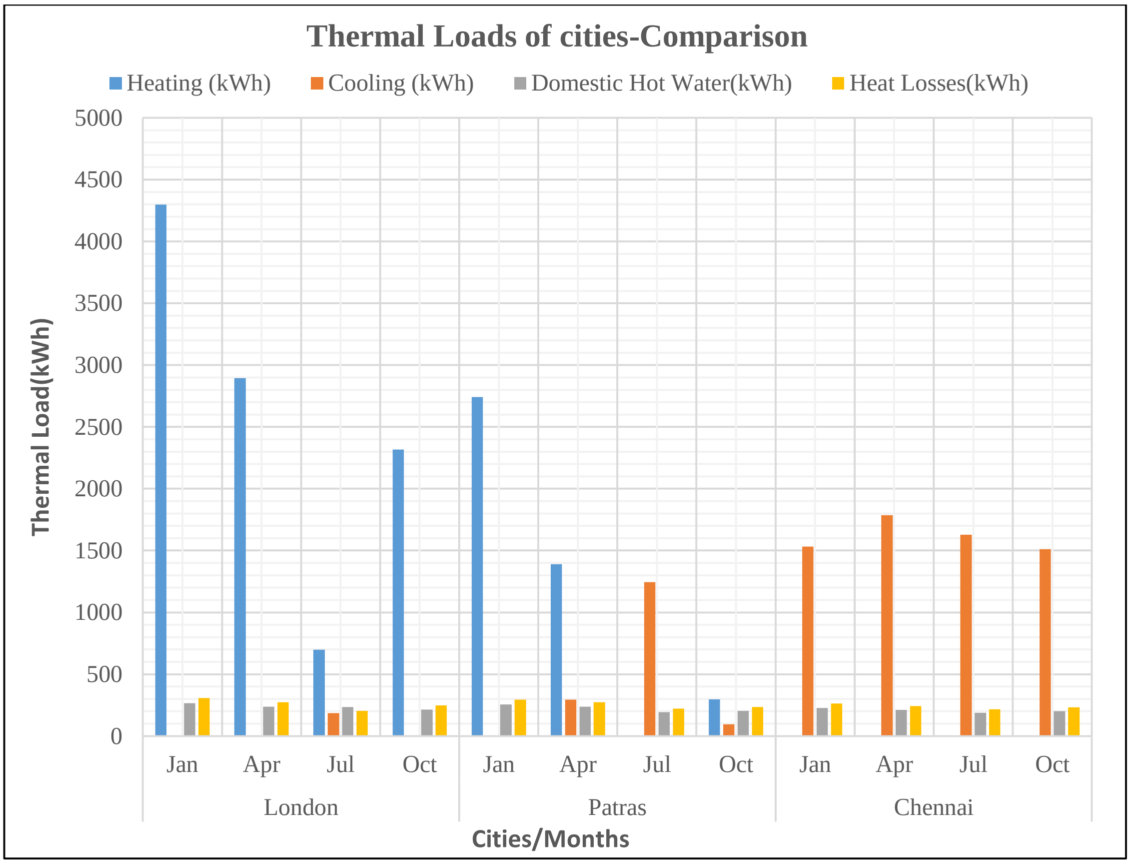


Figure 5-2: Plots of Thermals loads in 3 cities

5.5 Electric Loads of the building in 3 cities

To calculate the electric loads in the 3 cities,typical consumer appliances used in buildings along with their rated power and duty cycle(obtained from RetScreen)were considered. The hours of operation of each appliance was arbitrarily selected. However,the operating hours were selected with some considerations depending on the daylight duration and the ambient temperature.For example, as the ambient temperature is higher in Chennai compared to the other 2 cities, the hours of refrigeration was also selected higher . Also, as the daylight duration hours were longer for Chennai ,the hours of operation of lights was lesser in comparison to PatrasThe electric load demand is not so much important as the accurate sizing of the stand alone PV system to satisfy a certain load demand.Tables 5-25 to 5-27 present the daily average electric loads of the 3 cities for the seasonal months.

Table 5-25: Electric Load for seasonal months(London)

Description	Electricity load - typical	Qty.	Operating hours(h/m)				Rated Power	Duty cycle	Electric Load (kWh)			
	W		Jan	Apr	Jul	Oct	W	%	Jan	Apr	Jul	Oct
Electric blanket - double	120	1	60	25	13	35	120	100	7.20	3.00	1.50	4.20
Inkjet printer	13	1	15	15	15	15	13	100	0.20	0.20	0.20	0.20
Microwave oven	750 - 1200	1	10	10	10	10	750	100	7.50	7.50	7.50	7.50
Refrigerator	300 - 725	1	90	110	120	100	300	30	8.10	9.90	10.80	9.00
Clothes washer	350 - 500	1	20	20	20	20	350	80	5.60	5.60	5.60	5.60
Computer	200 - 300	1	30	30	30	30	250	100	7.50	7.50	7.50	7.50
Air-conditioner - window unit	750 - 1100	1	0	0	12	0	1,100	80	0.00	0.00	10.56	0.00
TV	80 - 300	1	15	15	15	15	100	100	1.50	1.50	1.50	1.50
Lights	80	3	80	60	60	70	80	100	19.20	14.40	14.40	16.80
Total(kWh)									56.80	49.60	59.56	52.30
Daily average Load(kWh)									1.83	1.65	1.92	1.69

Table 5-26: Electric Load for seasonal months(Patras)

Description	Electricity load - typical	Qty.	Operating hours(h/m)				Rated Power	Duty cycle	Electric Load(kWh)			
	W		Jan	Apr	Jul	Oct	W	%	Jan	Apr	Jul	Oct
Electric blanket - double	120	1	60	25	13	35	120	100	7.20	3.00	1.50	4.20
Inkjet printer	13	1	15	15	15	15	13	100	0.20	0.20	0.20	0.20
Microwave oven	750 - 1200	1	10	10	10	10	750	100	7.50	7.50	7.50	7.50
Refrigerator	300 - 725	1	90	110	120	100	300	30	8.10	9.90	10.80	9.00
Clothes washer	350 - 500	1	20	20	20	20	350	80	5.60	5.60	5.60	5.60
Computer	200 - 300	1	30	30	30	30	250	100	7.50	7.50	7.50	7.50
Air-conditioner - window unit	750 - 1100	1	0	0	20	0	1,100	80	0.00	0.00	17.60	0.00
TV	80 - 300	1	15	15	15	15	100	100	1.50	1.50	1.50	1.50
Lights	80	4	140	110	100	130	80	100	44.80	35.20	32.00	41.60
Total(kWh)									82.40	70.40	84.20	77.10
Daily Average Load(kWh)									2.66	2.35	2.72	2.49

Table 5-27: Electric Load for seasonal months(Chennai)

Description	Electricity load - typical	Qty.	Operating hours(h/m)				Rated Power	Duty cycle	Electric Load (kWh)			
	W		Jan	Apr	Jul	Oct	W	%	Jan	Apr	Jul	Oct
Inkjet printer	13	1	15	15	15	15	13	100	0.20	0.20	0.20	0.20
Microwave oven	750 - 1200	1	15	15	15	15	750	100	11.25	11.25	11.25	11.25
Refrigerator	300 - 725	1	90	110	240	120	300	30	8.10	9.90	21.60	10.80
Clothes washer	350 - 500	1	20	20	20	20	350	80	5.60	5.60	5.60	5.60
Computer	200 - 300	1	90	90	90	90	250	100	22.50	22.50	22.50	22.50
TV	80 - 300	1	15	15	15	15	100	100	1.50	1.50	1.50	1.50
Heat Pump	2,500	1	10	15	13	8	2,500	100	25.00	37.50	31.25	18.75
Lights	80	4	90	70	60	80	80	100	28.80	22.40	19.20	25.60
Total(kWh)									102.95	110.85	113.10	96.20
Daily Average Load(kWh)									3.32	3.69	3.65	3.10

The following plot shows the electric loads across the 3 cities in the four seasonal months.

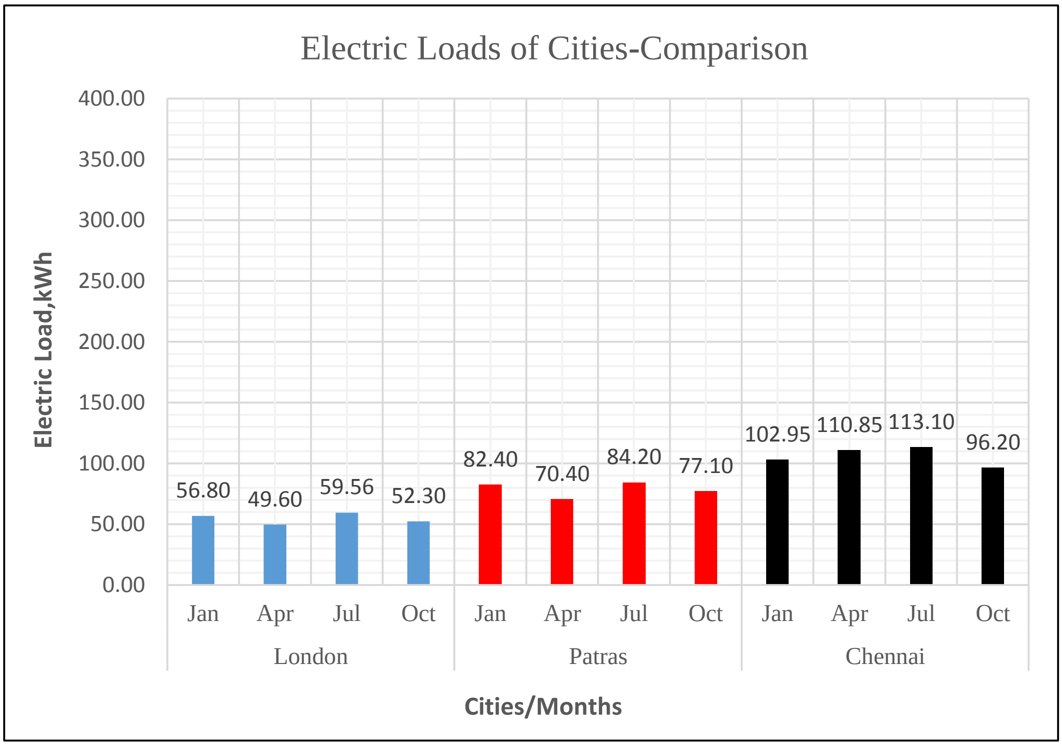


Figure 5-3: Electric Loads of 3 cities - Bar chart

Chapter 6

SIZING OF RENEWABLE SYSTEMS FOR LOADS

The different options by which the loads(thermal and electric)calculated in the previous chapter can be satisfied by using Renewable systems are as follows :

1.Solar Collector (Space Heating and Domestic Hot Water)

2. a) Heat Pump (Space Heating ,Domestic Hot Water and Cooling)

   b) Heat Pump assisted by Solar Collector (Space Heating ,Domestic Hot Water and Cooling)

3. Absorption Chillers

4. a) Photo-Voltaics (Stand alone or Grid Connected)

   b) PV/T

6.1 Calculation of Output of the Solar Collector

One of the options to meet the thermal loads is by the use of solar collectors.The design of the solar collector is made considering the month where the maximum thermal load is to be satisfied.It can be seen from Table 5-24 that for London,the thermal load demand is maximum for January with a value of 4872.61 kWh.

For the purpose of this analysis, the solar collector that is considered to meet the thermal loads is a flat plate solar collector(Manufacturer WOLF GmbH) which has the following properties .

Table 6-1:Properties of Flat plate solar Collector

Parameter	Value
Aperture Area	2m^2 per collector
Overall Area	2.3m^2 per collector
Brand Name	Topson
Model Number	F3-1

Heat Losses Coefficient,F_RU_L	4.3 W/m^2.ºC
Optical Efficiency,$F_R(\tau\alpha)$	0.82
Absorber	Solid copper with highly selective coating for very high yield
Insulation	Mineral Thermal Insulation(60mm thick)
Application	Hot water,Space Heating,pool etc.,

A daily simulation was performed to calculate the Solar Collector output.The following equations were utilized to assist the calcuation.

$$q_{u,\Delta\tau} = F_R'.\frac{\left[H_n(\tau\alpha) - U_L.\left(T_{s,i} - T_a\right).\Delta\tau\right]}{1 + F_R'.\frac{U_L}{\left(2.m.C_p\right)_s}.\Delta\tau} \qquad 6\text{-}1$$

$$T_{s,f} = T_{s,i} + \frac{q_{u,\Delta\tau}}{2.\left(m.C_p\right)_s} \qquad 6\text{-}2$$

$q_{u,\Delta\tau}$ is the thermal output stored into the tank by the fluid flow per unit area of the Solar Collector system.

H_n is the solar radiation intensity for the interval.

$T_{s,i}$ is the temperature of water in the tank at the beginning of the time period τ and $T_{s,f}$ is the corresponding temperature at end of the period (τ + Δτ)

T_a is the average ambient temperature during the time interval (τ,τ + Δτ)

m is the capacity of the Hot water tank.

Table 6-2: Monthly Output of the Solar Collector (London)

Flat plate Collector Area(m^2)	$F_R U_L$(W/m^2 K)	$F_R(\tau\alpha)$	Optimal angle of inclination for January(deg)	Temperature of the tank at 8:30AM($^\circ C$)	Hot water Tank Capacity(kg/m^2)	
2	4.3	0.82	68	20	50	
Hour	T_a($^\circ C$)	H_T(KJ/m^2)	q_u(KJ/m^2)	T_{si} ($^\circ C$)	T_{sf} ($^\circ C$)	$\eta = q_u/H_T$
8:30AM-9:30AM	4	500.4	156.84	20.00	20.38	0.31
9:30AM-10:30AM	4.5	770.4	372.20	20.38	21.27	0.48
10:30AM-11:30AM	5.6	933.3	504.13	21.27	22.47	0.54
11:30AM-12:30PM	6.5	986.4	541.55	22.47	23.77	0.55
12:30PM-1:30PM	7	933.3	487.69	23.77	24.93	0.52
1:30PM-2:30PM	6.8	770.4	338.48	24.93	25.74	0.44
2:30PM-3:30PM	6.5	500.4	108.42	25.74	26.00	0.22
Total Solar Collector Output per day(KJ/m^2)			2509.30			
Total Solar Collector Output for the month(kWh)			43.22			

In Table 6-2,the values of the Heat Losses coefficient,$F_R U_L$ and the optical efficiency,$F_R(\tau\alpha)$are manufacturer values for the Flat plate solar collector.The optimal angle of inclination was obtained from PVGIS database for the month of January.The initial temperature of the water inside the tank and the capacity of the hot water tank were assumed to be 20°C and 50kg/m^2 respectively.The ambient temperatures in column 2 of Table 6-2 were obtained from PVGIS .By means of equations 6-1 and 6-2 all the corresponding values for each of the parameters were calculated.The Solar collector output per day was obtained by the summation of the hourly values of solar collector output.Finally, the solar collector output was determined for the month of January for London.

The procedure in the above paragraph is repeated to determine the output of the solar collector located in Patras and the results are tabulated in Table 6-3.

Table 6-3: Monthly Output of the Solar Collector(Patras)

Flat plate Collector Area(m^2)	*$F_R U_L$(W/m^2 K)*	*$F_R(\tau\alpha)$*	*Optimal angle of inclination for January(deg)*	*Temperature of the tank at 7:30AM($^\circ C$)*	*Hot water Tank Capacity(kg/m^2)*	
2	4.3	0.82	61	20	50	
Hour	T_a(°C)	H_T(KJ/m^2)	q_u(KJ/m^2)	T_{si} (°C)	T_{sf} (°C)	$\eta = q_u/H_T$
7:30AM-8:30AM	9.6	561.6	288.82	20.00	20.69	0.51
8:30AM-9:30AM	11.5	1335.6	918.89	20.69	22.89	0.69
9:30AM-10:30AM	12.3	1888.2	1334.96	22.89	26.08	0.71
10:30AM-11:30AM	12.4	2234.7	1562.77	26.08	29.82	0.70
11:30AM-12:30PM	12.6	2350.8	1601.75	29.82	33.65	0.68
12:30PM-1:30PM	12.3	2234.7	1448.27	33.65	37.12	0.65
1:30PM-2:30PM	12	1888.2	1118.09	37.12	39.79	0.59
2:30PM-3:30PM	11.5	1335.6	633.74	39.79	41.31	0.47
3:30PM-4:30PM	10.9	621.9	37.82	41.31	41.40	0.06
Total Solar Collector Output per day(KJ/m^2)			8945.11			
Total Solar Collector Output for the month(kWh)			154.05			

Following the calculation of the solar collector output, the collector area(m^2) required for meeting a definite fraction of the thermal load,f of January can now be computed. This is obtained by calculating the thermal load corresponding to each fraction and dividing the value by the solar collector output of the corresponding city.The results for both cities are given in Table 6-4.

Table 6-4:Collector Area and quantity of Collectors(London & Patras)

S.No	% of Thermal loads met by Solar Collector(Space heating +Hot water + Heat Losses)	Minimum Collector Area(m^2) required for Covering the Loads		No. of Collectors(Rounded off to nearest whole number)	
		London	Patras	London	Patras
1	30	23	6	12	3
2	40	34	9	17	5
3	50	45	11	23	6
4	60	56	13	28	7
5	70	68	15	34	8

6	80	79	17	40	9
7	90	90	19	45	10
8	100	101	21	51	11

6.2 Cooling Equipment selection for Cooling Loads(Chennai)

One of the options to meet the cooling demand is by use of Heat Pumps.This section outlines the procedure involved in the selection of the appropriate Heat Pump. The Heat Pump is an air source Heat Pump. Air source heat pump systems are not a common choice in cold climates with a large heating load.However, an air source heat pump is a likely choice for climates where the heating load is much smaller than the cooling load i.e., for cases like Chennai .

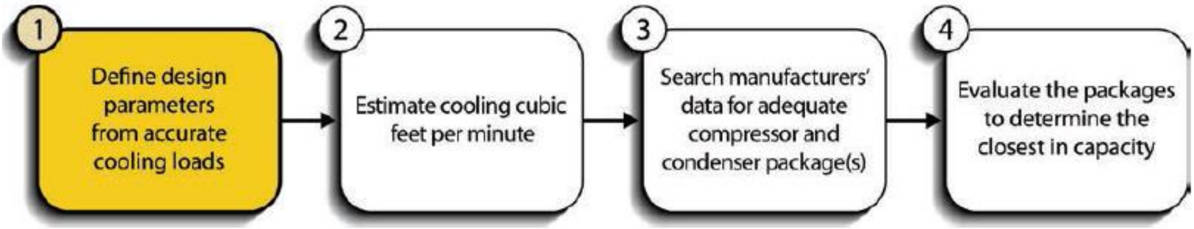


Figure 6-1: Cooling equipment selection steps

(Source : Manual S,2013)

As seen from Fig.6-1,the primary step is to define the design parameters.Since the heat pump selection is made based on the month which has the maximum cooling Load for Chennai i.e., April . The design cooling load is the amount of heat energy to be removed from a house by the HVAC equipment to maintain the house at indoor design temperature when worst case outdoor design temperature is being experienced.

There are two types of cooling loads namely Sensible Cooling Load and Latent Cooling Load. The sensible cooling load refers to the dry bulb temperature of the building and the latent cooling load refers to the wet bulb temperature of the building.The Latent Cooling load is considered to be 30% of the total cooling Load(*Manual S*) and the values given in the following table are that at Solar noon for April (Refer Table 5-23).The other design parameters are also defined based on the considered region(in this case Chennai).

Loads	Heating Load	Nil
	Sensible Cooling Load	19319.47 Btu/hr (5661.97W/hr)
	Latent Cooling Load	1179.727 Btu/hr (345.74W/hr)

Outdoor Conditions	Cooling-Dry Bulb Temperature	87.62^{o}F (30.9 ^{o}C)
	Heating Dry-Bulb Temperature	2^{o}F (-16.67 ^{o}C)

Indoor Conditions	Cooling-Dry Bulb Temperature	72^{o}F (22^{o}C)
	Cooling-Wet Bulb Temperature	63^{o}F (17 ^{o}C)
	Heating Dry-Bulb Temperature	66^{o}F (18.8 ^{o}C)

Air flow Estimates	Cubic Feet per minute(cfm)	To be determined

To search the manufacturer’s expanded performance data, an initial estimate of the required cfm airflow is needed. The estimated cfm airflow is used only to narrow down the equipment choices from the manufacturer’s data and will likely be higher than the actual cfm used for the design.

The detailed procedure to estimate a target cfm is described in Manual S. Manual S instructs the designer to use the Sensible Heat Ratio (SHR) value to determine the desired room-air to supply-air Temperature Difference (TD) in degrees Fahrenheit.

$$SHR = \frac{Sensible\ Load}{Total\ Load} \qquad 6\text{-}3$$

Manual S shows the relationship of an SHR range to TD value that is compatible with the sensible and latent loads. The column “LAT” is the temperature of air leaving the coil, and the column “Room db” is the indoor conditions dry-bulb temperature .The difference between the two is the TD value.

Table 6-5: TD Value (from Manual S)

Sensible Heat Ratio versus TD Value			
SHR	LAT(^{o}C)	Room db(^{o}C)	TD(^{o}C)
Below 0.80	53	75	22
0.80 to 0.85	55	75	20
Above 0.85	57	75	18

Once the TD value is known, the estimated cfm target can be calculated using equation 6-4

$$cfm\,Target = \frac{Sensible\ Load}{1.1\ X\ TD} \qquad 6\text{-}4$$

The number 1.1 in the denominator of equation 6-4 represents an air properties constant associated with elevations lower than 1,500 feet.Since Chennai is located at an elevation of 200ft the above constant is appropriate.

From equation 6-3

SHR = (Sensible Load/Total Load) = (19319.47Btu/hr/20499.197Btu/hr) = 0.94

From the TD value Table 6-5, the TD value for SHR = 0.94 is 18 .Using these values in equation 6-4 ,the cfm target is :

Cfm target = Sensible Load/(1.1 X TD) = (19319.47/1.1*18) = 975.73

Step 3, highlighted in Fig. 6-1, is to search the manufacturer's data for an adequate cooling equipment package. Considering that 12000 Btu/h is equivalent to 1 nominal ton of cooling, the 20499.1997 Btu/h total cooling load for the building in Chennai leads to a 2-ton nominal size cooling system as the target size to begin the equipment search.

The Entering Wet-Bulb Temperature(EWB) temperature for the indoor coil can be determined on the sea-level psychometric chart for our reference conditions of $22^{o}C \simeq 72°F$ indoor design dry-bulb temperature and 62.5% relative humidity for April(Refer Table II-A of Appendix II), as shown in Fig. 6-2.

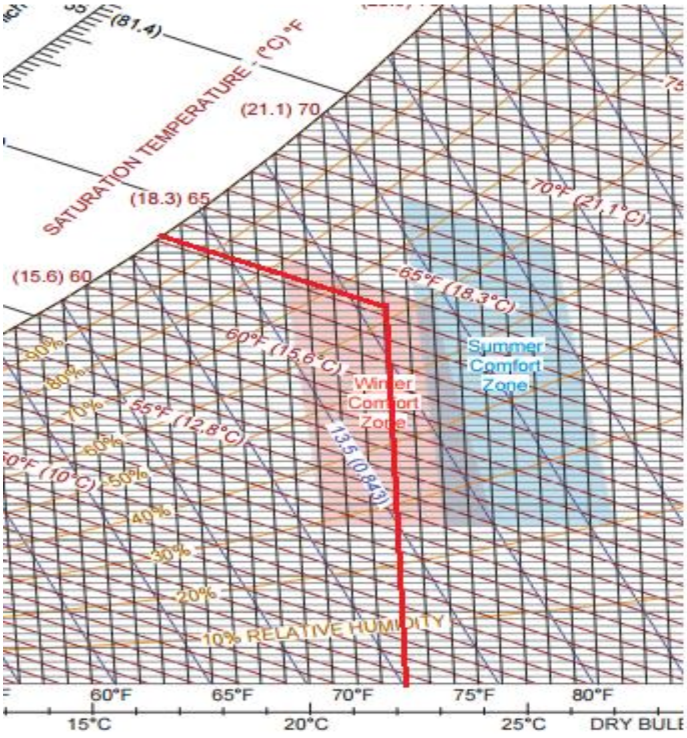


Figure 6-2: Wet-bulb temperature on sea-level psychometric chart

HVAC equipment manufacturers make available tabulated performance data that are used to select the equipment based on the loads and design conditions. Table 6-6 provides an example of expanded performance data for air-air cooling equipment (cooling-only, or heat pump).

Table 6-6: Expanded Performance Data for Cooling with an Air-Cooled Condenser or Heat Pump (Source :Manual S**)**

EWB °F	Cfm	Outdoor DB 85 °F				Outdoor DB 90 °F				Outdoor DB 95 °F				Outdoor DB 100° F			
		TC Btuh	CSHR			TC Btuh	CSHR			TC Btuh	CSHR			TC Btuh	CSHR		
			EDB °F				EDB °F				EDB °F				EDB °F		
			75	80	85		75	80	85		75	80	85		75	80	85
59	1,000	27,205	0.94	1.00	1.00	26,080	0.97	1.00	1.00	24,955	0.99	1.00	1.00	23,830	1.00	1.00	1.00
	1,125	27,621	0.98	1.00	1.00	26,496	1.00	1.00	1.00	25,371	1.00	1.00	1.00	24,246	1.00	1.00	1.00
	1,250	28,038	1.00	1.00	1.00	26,913	1.00	1.00	1.00	25,788	1.00	1.00	1.00	24,663	1.00	1.00	1.00
63	1,000	29,205	0.75	0.88	1.00	28,080	0.78	0.91	1.00	26,955	0.80	0.93	1.00	25,830	0.83	0.96	1.00
	1,125	29,621	0.79	0.92	1.00	28,496	0.82	0.95	1.00	27,371	0.84	0.97	1.00	26,246	0.87	1.00	1.00
	1,250	30,038	0.83	0.96	1.00	28,913	0.86	0.99	1.00	27,788	0.88	1.00	1.00	26,663	0.91	1.00	1.00
67	1,000	31,205	0.56	0.69	0.82	30,080	0.59	0.72	0.85	28,955	0.61	0.74	0.87	27,830	0.64	0.77	0.90
	1,125	31,621	0.60	0.73	0.86	30,496	0.63	0.76	0.89	29,371	0.65	0.78	0.91	28,246	0.68	0.81	0.94
	1,250	32,038	0.64	0.77	0.90	30,913	0.67	0.80	0.93	29,788	0.69	0.82	0.95	28,663	0.72	0.85	0.98

In Table 6-6,EWB = Entering Wet Bulb Temperature ,EDB = Entering Dry Bulb Temperature, Cfm = Blower Cfm setting ,TC = Total cooling capacity (sensible plus latent), CSHR = Coil sensible heat ratio = Sensible Btuh / Total Btuh

In Chennai ,the EWB as determined on the sea level psychrometric chart(Fig.6-2) is 63^{o}F, Outdoor DBT is 87.5^{o}F $\simeq 90^{o}$F ,Indoor DBT is 72^{o}F $\simeq 75^{o}$F and the blower cfm is 975 which is closer to 1000 in Table 6-6 .

Hence the total Cooling Capacity required for the Heat Pump = 26,955 Btuh = 7.9kWh $\simeq$ **8kWh**

The Coefficient of Performance of the selected Heat Pump is given by the following equation:

$$COP = \frac{Cooling\ (or\ Heating) provided}{Work\ Consumed\ by\ Heat\ Pump} \tag{6-5}$$

A Heat Pump with a cooling capacity of 8kWh will have a rated electrical power consumption by Fan coils,Compressor etc., of 2.5kWh (**Source :Energy.Gov**) .Hence the COP of the Heat Pump will be :

COP = 8/2.5 = **3.2**

6.3 Sizing of Stand-alone PV for meeting the Electric Loads

To design a stand-alone PV system required to cover the electric Loads of the Building the following steps are required .

Step 1:

The scenario for which the PV System has to cover the daily energy demand,the electrical appliances and their daily hours of operation and months of usage are decided.The Stand-alone PV system has been sized in Chennai for the month with the maximum electric Load and the worse month in terms of Solar-irradiation(Nov).

Step 2 :

The appliances that are used in the building along with their rated power and operating hours are entered to determine the daily Load Q_L are in Table 5-27.

As seen from Table 5-27,the monthly electricity consumption for April is 110.85kWh and hence the daily load, Q_L is 3.69kWh.

Note :The operating hours of all the appliances are given in hours per month .

Step 3 :

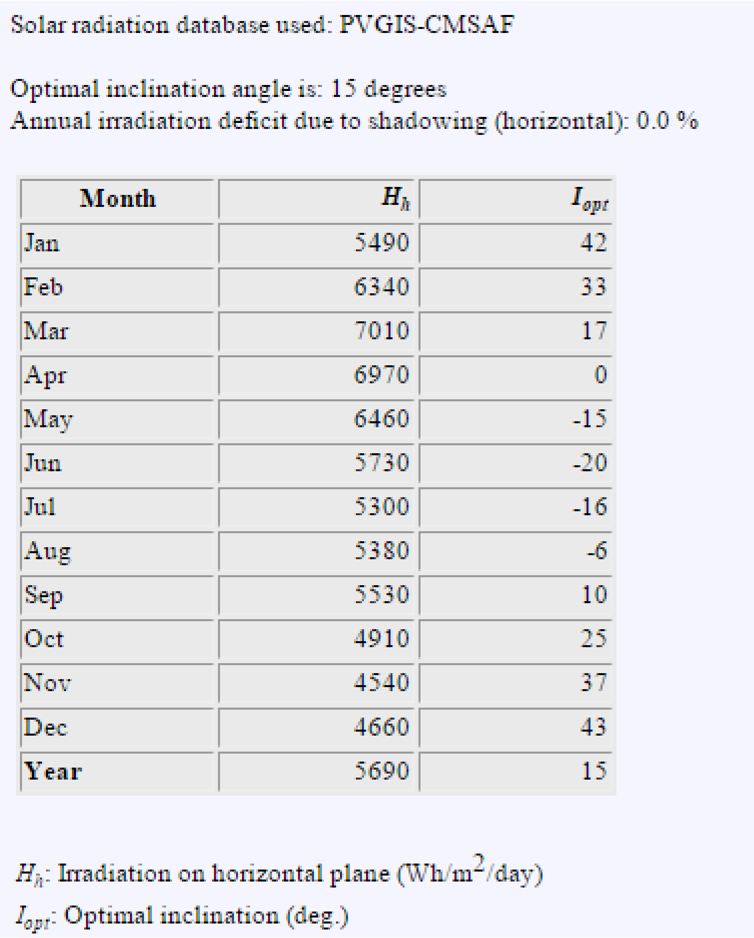
The PV installation details are decided.The building under consideration is located in an open ground with minimal obstacles/objects.Hence the effects of shading are ignored.

A free PV system is choosen over a BIPV.

The optimal inclination angle of the PV for maximum incident solar radiation throughout the year is **15°** and the daily irradiation on the horizontal is **5690W/m^2.**The above values are obtained from PVGIS database as shown :

Table 6-7: Irradiation on the Horizontal and Optimal inclination angle for Chennai

(Source :PVGIS)



Solar radiation database used: PVGIS-CMSAF

Optimal inclination angle is: 15 degrees
Annual irradiation deficit due to shadowing (horizontal): 0.0 %

Month	H_h	I_{opt}
Jan	5490	42
Feb	6340	33
Mar	7010	17
Apr	6970	0
May	6460	-15
Jun	5730	-20
Jul	5300	-16
Aug	5380	-6
Sep	5530	10
Oct	4910	25
Nov	4540	37
Dec	4660	43
Year	5690	15

H_h: Irradiation on horizontal plane (Wh/m^2/day)
I_{opt}: Optimal inclination (deg.)

Step 4 :

The average Peak Solar Hours (PSH)of the day are determined for the worse month in terms of incident solar energy.PSH is defined as the time length in hours/day for a given day such that the solar intensity is constant at 10^{3}W/m^2.The PSH value will be such that

H = **(PSH)**h/day.**10^3**W/m^2 .It can be seen from Table 6-7 that the average PSH for the worse month of sizing (November) is **4.54hrs.**

The average conversion factor ,R of the solar radiation from the horizontal to the inclined is calculated.

$$H_{T\ avg} = H_{avg} \,.\, R_{avg} \qquad 6\text{-}6$$

$R_{avg} = H_{T\ avg} / H_{avg} = 5060/4540$

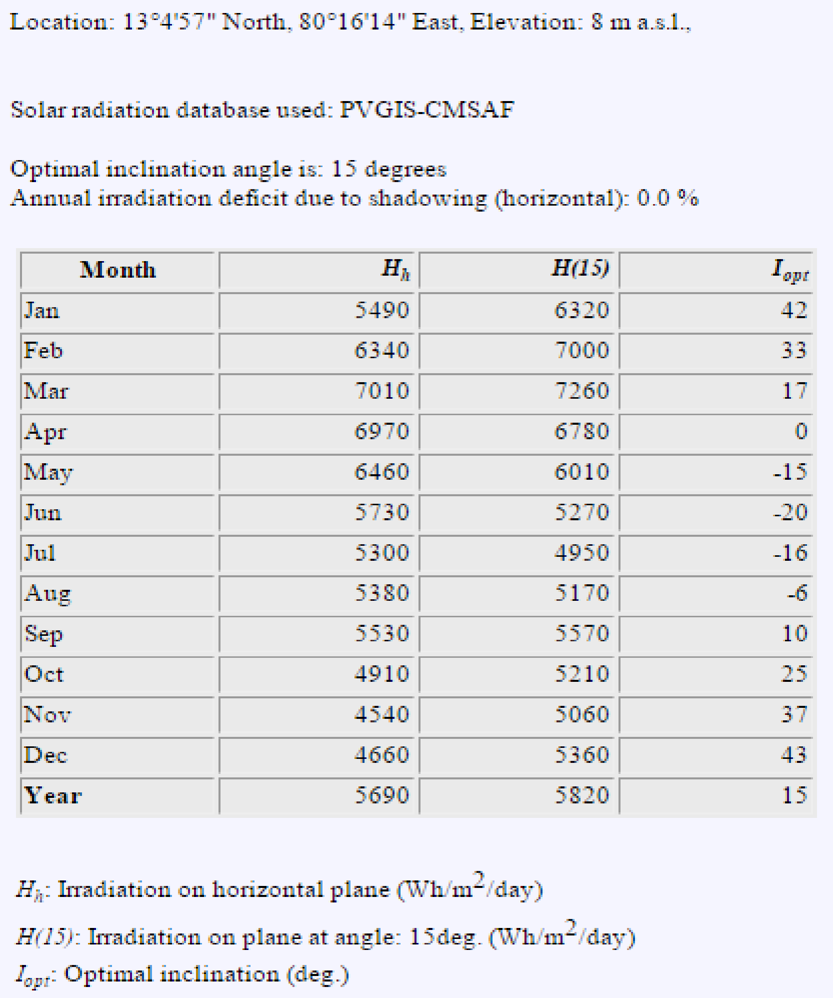
$R_{avg} = 1.114$

The $PSH_{avg}.R_{avg}$ is determined through the mean monthly daily solar irradiation H_{Tavg} obtained from **PVGIS** for the worse month (November) and is

$PSH_{avg}.R_{avg} = (4.54x1.114) =$ **5.06**

Table 6-8: Irradiation at the Optimal inclination angle for Chennai

(Source : PVGIS)



Location: 13°4'57" North, 80°16'14" East, Elevation: 8 m a.s.l.,

Solar radiation database used: PVGIS-CMSAF

Optimal inclination angle is: 15 degrees
Annual irradiation deficit due to shadowing (horizontal): 0.0 %

Month	H_h	$H(15)$	I_{opt}
Jan	5490	6320	42
Feb	6340	7000	33
Mar	7010	7260	17
Apr	6970	6780	0
May	6460	6010	-15
Jun	5730	5270	-20
Jul	5300	4950	-16
Aug	5380	5170	-6
Sep	5530	5570	10
Oct	4910	5210	25
Nov	4540	5060	37
Dec	4660	5360	43
Year	5690	5820	15

H_h: Irradiation on horizontal plane (Wh/m^2/day)

$H(15)$: Irradiation on plane at angle: 15deg. (Wh/m^2/day)

I_{opt}: Optimal inclination (deg.)

Step 5:

The autonomy factor d for the non-critical loads considered in step 2 is determined.In this scenario, the loads are all non-critical and hence it is satisfactory if the demands are met **95%** of the time .

$$d_{n\text{-}cr} = -0.48*PSH_{min} + 4.58(\text{days}) \qquad 6\text{-}7$$

The minimum PSH of the sizing month is obtained from SoDa Database for a period of 10-15 years(Refer Table II-A ,Appendix II).It is to be noted here that the mean monthly daily value of irradiation for the sizing month November is given in J/Cm^2 i.e.,**1642 J/Cm^2**.Hence the value is converted to Wh/m^2 by multiplying by 2.778 .

Hence PSH_{min} = 1642*2.778/1000 = **4.56hrs/day**

Hence $d_{n\text{-}cr}$ = -0.48*4.56 + 4.58(days)

$d_{n\text{-}cr}$ = 2.39 $\underset{\sim}{}$~ 3 days

Step 6 :

The installed Peak power P_m is determined :

$$(P_m + \delta P_m)PSH_{avg}.R_{avg}.\eta_{inv}.\eta_{ch}.\eta_{cab}.\eta_{bat} = Q_L.d \qquad 6\text{-}8$$

Typical Values η_{inv} = 95%, η_{bat} = 85%, η_{ch} = 95%, η_{cab} = 98%

δP_m due to the temperature developed in the PV is calculated :

PV Temperature T_{PV} is estimated through the following expression.

$$T_{PV} = T_a + f.I_T \qquad 6\text{-}9$$

Where f=0.03^{o}C/(W/m^2) for free standing PV system.The values of T_a and I_T for the sizing month are determined from PVGIS by considering Clear Sky Global Irradiance and finding the average of irradiance and temperature at **12,12 – PSH /2** and **12+PSH/2** from the mean monthly hourly profile of solar irradiance and ambient temperature respectively as shown in Fig.6-3.

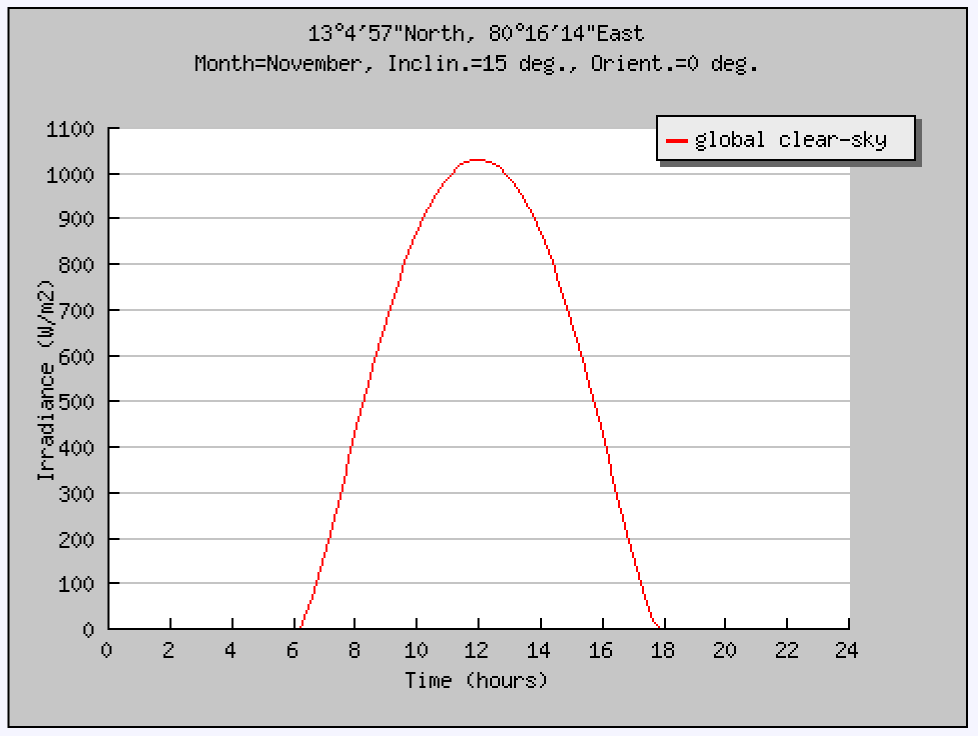


Figure 6-3:Irradiance profile(daily)for Chennai

(Source : PVGIS)

The values of T_a and I_T were calculated as **26.1°C** and **853.33W/m²**

$T_{PV} = 26.1 + 0.03*853.33$

$\mathbf{T_{PV} = 51.7^oC}$

The temperature coefficient of power is assumed to be -0.45%/ °C

$(\delta P_m/P_m) = -0.0045(51.7-26.1)$

$(\delta P_m/P_m) = -0.1152 \Rightarrow \mathbf{\delta P_m = -0.115P_m}$

Substituting the above in equation 6-8

$(P_m-0.115P_m)*5.06*0.95*0.95*0.98*0.85 = 3.69*10^3*3$

$0.885P_m = 2910.083$

$P_m = 3288.23$ W = **3.29kW**

Step 7 :

The installed Battery Capacity is determined by equation 6-10,

$$C = (d.Q_L)/(V.DOD.\eta_{inv-ch}.\eta_{bat}) \qquad 6\text{-}10$$

$= 3*3.69*10^3/(24*0.80*0.95*0.85)$

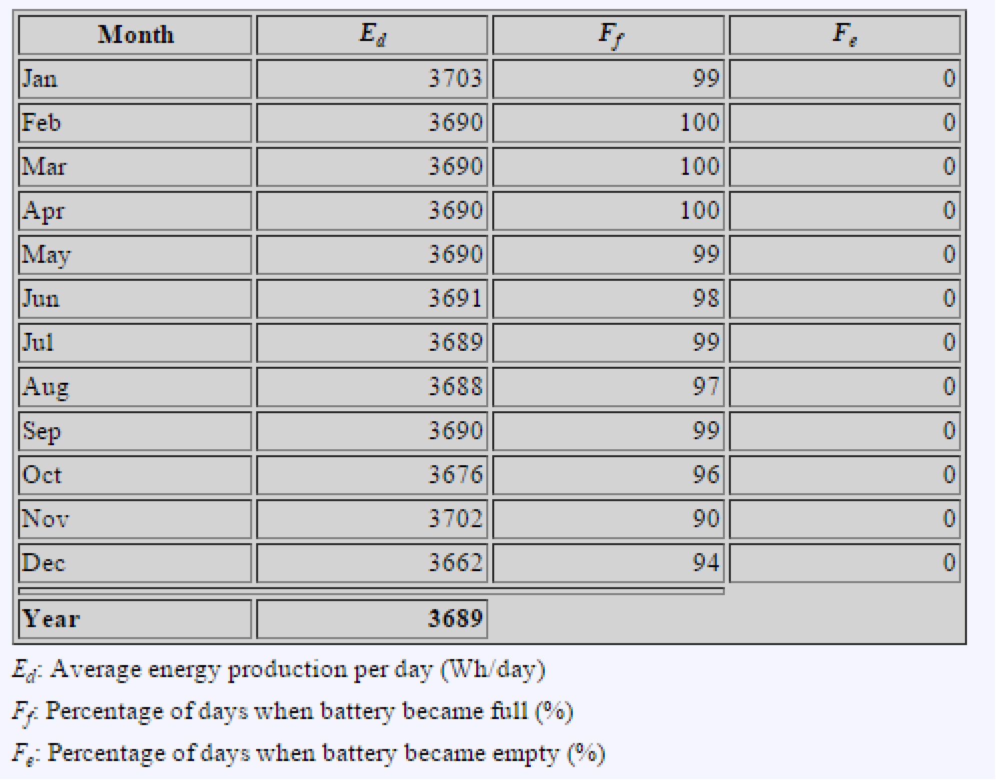
$C = 714$ Ah

The batteries are located in a room where the temperature is 25°C.Hence the correction factor is 1.

Step 8 :

The performance of the stand-alone PV system designed is checked in **PVGIS** Database by entering the values of the installed peak power P_m , battery capacity C and average daily load Q_L estimated for the sizing month(November) .The following results were obtained :

Table 6-9:Annual Stand alone PV performance with days of autonomy 3



Month	E_d	F_f	F_e
Jan	3703	99	0
Feb	3690	100	0
Mar	3690	100	0
Apr	3690	100	0
May	3690	99	0
Jun	3691	98	0
Jul	3689	99	0
Aug	3688	97	0
Sep	3690	99	0
Oct	3676	96	0
Nov	3702	90	0
Dec	3662	94	0
Year	**3689**		

E_d: Average energy production per day (Wh/day)

F_f: Percentage of days when battery became full (%)

F_e: Percentage of days when battery became empty (%)

As seen from Table 6-9 ,the system appears to be over-sized since there are no failures.It may be noted that a system failure of upto 5% for non-critical loads is permissible.

Hence, the days of autonomy d is reduced from **3** to **2** and the installed Peak Power P_m and the battery capacity C are calculated again.

$(P_m - 0.115P_m)*5.06*0.95*0.95*0.98*0.85 = 3.69*10^3*2$

$0.885P_m = 1940.043$

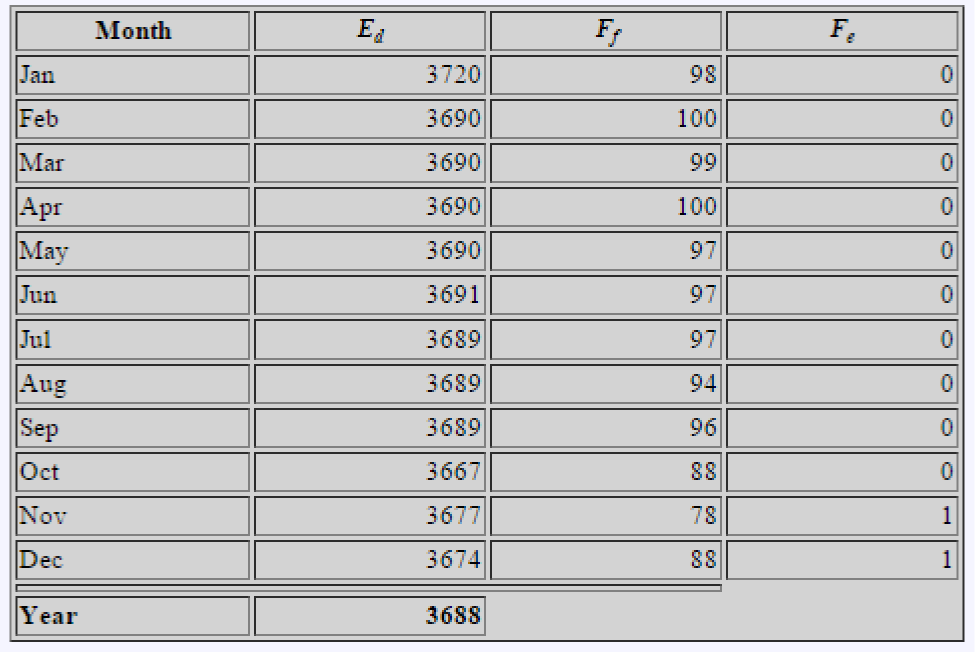
$P_m = 2192.15$ W = **2.19 kW**

Battery Capacity, $C = 2*3.69*10^3/(24*0.80*0.95*0.85)$

C = 476 Ah

The above values are again entered in PVGIS to check the failure rate of the Stand-alone PV System**(SAPV)**and the following was obtained **:**

Table 6-10:Annual Stand alone PV performance with days of autonomy 2



Month	E_d	F_f	F_e
Jan	3720	98	0
Feb	3690	100	0
Mar	3690	99	0
Apr	3690	100	0
May	3690	97	0
Jun	3691	97	0
Jul	3689	97	0
Aug	3689	94	0
Sep	3689	96	0
Oct	3667	88	0
Nov	3677	78	1
Dec	3674	88	1
Year	**3688**		

As seen from Table 6-10,the total system failure is 2% .As the load is non-critical ,the choosen values are optimal.

<u>Note</u>: It is to be mentioned here that as the appliances are arbitrarily decided, the hourly consumption profile is not known and the default night-based hourly consumption profile of PVGIS as shown in Fig.6-4 is utilized in the above scenario.

<u>Step 9</u> :

For the final estimated P_m and C,the number of PV modules and batteries to be connected are determined .

a)Bio-195 module is choosen and the number of modules N_{PV} required are calculated .

$N_{PV} = P_{m,gen}/P_{m,module} = 2192.15/195$

$= 11.24 \simeq 12$

The number of modules to be connected in series is calculated based on the DC voltage V for Power Transfer .

$N_{pv,s} = V/V_m$

Temperature coefficient of Voltage for the above module is -0.1801 V/°C(as provided by the manufacturer) .Hence the Voltage V_m corrected to the temperature of the PV module is

$V_m = 36.94 – 0.1801*(51.7 – 25)$

$V_m = 32.13V$

Therefore, $N_{PV,S} = 24/32.13 = 0.747 \simeq 1$

The number of strings to be connected in parallel is $N_{pv,p} = N_{pv} / N_{pv,s}$

$N_{pv,p} = 12/1 = 12$

b)**12V 100AH Lithium Ion** batteries are selected with DOD 80%

The number of batteries to be connected in series ,$N_{b,s} = V/V_b =24/12$

$N_{b,s} = 2$

The number of strings to be connected in parallel are $N_{b,p} =C/C_b = 476/100$

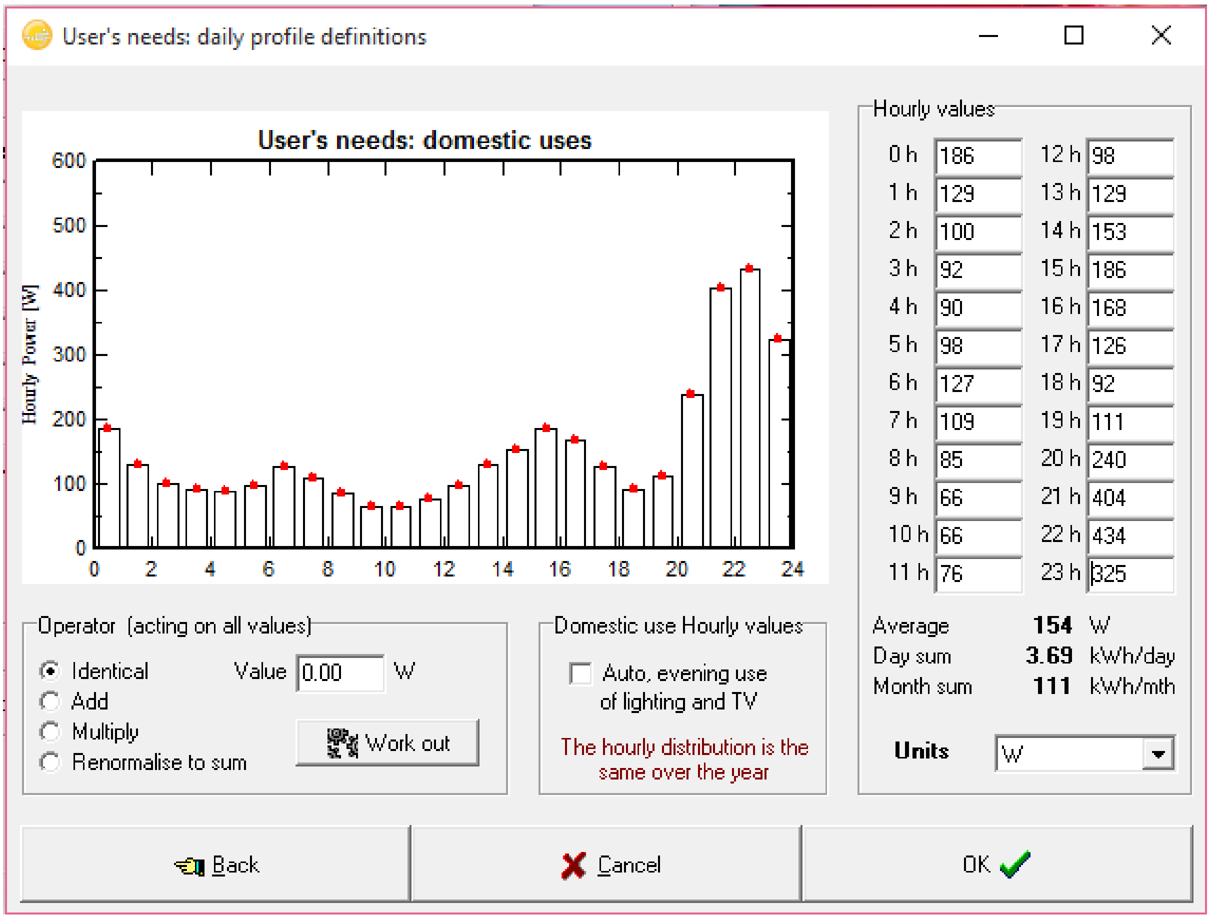
$N_{b,p} = 4.76 \simeq 5$

The corrections due to the charge/discharge rate are calculated

$$f_{b,ch/disch} = i_{ch/disch(as\ recommended)}/i_{ch,disch(due\ to\ the\ load\ profile)} \tag{6-11}$$

The recommended upper value for charge/discharge is C/10 = [5*100]/10 = 50 A

The hourly profile of the appliances is given below :



Hourly values

0 h	186	12 h	98
1 h	129	13 h	129
2 h	100	14 h	153
3 h	92	15 h	186
4 h	90	16 h	168
5 h	98	17 h	126
6 h	127	18 h	92
7 h	109	19 h	111
8 h	85	20 h	240
9 h	66	21 h	404
10 h	66	22 h	434
11 h	76	23 h	325

Average **154** W
Day sum **3.69** kWh/day
Month sum **111** kWh/mth

Units W

Operator (acting on all values)
● Identical
○ Add
○ Multiply
○ Renormalise to sum
Value 0.00 W

Domestic use Hourly values
☐ Auto, evening use of lighting and TV
The hourly distribution is the same over the year

Figure 6-4:Hourly Consumption profile of the selected Loads

From the default hourly load profile as obtained from PVGIS,the maximum value of discharge current is found to be $0.1175*3.69*10^3/(24*0.95) = 19.01$A which is less than the recommended value of discharge.

However, the rate of charging is (number of panels *I_m of the module) = 12*5.28 = 63.36A which is more than the recommended value of charging.Hence a correction factor is imposed

$f_{b,ch/disch} = 50/63.36 = 0.789$

The Corrected Battery Capacity $C_{cor} = 476/0.789 = 603.29$Ah

C_{cor} = 603.29 Ah

Therefore the actual number of Battery strings in parallel is 603.29/100 = 6.03 ~ **6**

Step 10 :

The stand-alone PV system has been designed for the scenario considered and the following are the sizing details for the installation in Chennai :

Table 6-11: Stand alone PV system chennai design details

General	Battery Details		PV Panel details	
Installed Peak Power,P_m= **2.19kW**	Total Capacity(Corrected), C	**600 Ah**	Total Number of Panels,N_{PV}	**12**
Days of Autonomy,d=**2**	Number of Batteries in series,$N_{b,s}$	**2**	Number of Panels in series,$N_{pv,s}$	**1**
	Number of Battery strings in parallel, $N_{b,p}$	**6**	Number of Strings in Parallel, $N_{pv,p}$	**12**
	Battery	**12V 100AH** Lithium Ion	Module	**Bio-195**(Peak Power 195W)

The above procedure is also adopted for the building in London and Patras and the sizing details tabulated as follows :

Table 6-12: Stand alone PV system(London) design details

General	Battery Details		PV Panel details	
Installed Peak Power,P_m= **8.8kW**	Total Capacity(Corrected), C	**2400 Ah**	Total Number of Panels,N_{PV}	**46**
Days of Autonomy,d=**4**	Number of Batteries in series,$N_{b,s}$	**2**	Number of Panels in series,$N_{pv,s}$	**1**
	Number of Battery strings in parallel, $N_{b,p}$	**24**	Number of Strings in Parallel, $N_{pv,p}$	**46**
	Battery	**12V 100AH** Lithium Ion	Module	**Bio-195**(Peak Power 195W)

Table 6-13:Stand alone PV system(Patras) design details

General	Battery Details		PV Panel details	
Installed Peak Power,P_m= **3.8 kW**	Total Capacity(Corrected), C	**1000 Ah**	Total Number of Panels,N_{PV}	**20**
Days of Autonomy,d=**3**	Number of Batteries in series,$N_{b,s}$	**2**	Number of Panels in series,$N_{pv,s}$	**1**
	Number of Battery strings in parallel, $N_{b,p}$	**10**	Number of Strings in Parallel, $N_{pv,p}$	**20**
	Battery	**12V 100AH** Lithium Ion	Module	**Bio-195**(Peak Power 195W)

6.4 Sizing of Stand-alone PV using a stochastic approach

An extensive,thorough and in-depth analysis comprising hourly data for each of the days and for all days in the month of December was carried out for London ,Patras and November for Chennai .The sizing of the PV was done considering these months since this is the worse month in terms of solar radiation for the respective city and if the PV system is designed to meet the loads for this month,it is more likely to meet the loads for the other months where the solar radiation is better.The following equations were utilized in the analysis(*Kaplani and Kaplanis 2012*) .

$$I_T = I.R \tag{6-12}$$

$$R = \left(1-\frac{I_d}{I}\right).R_b + \frac{I_d}{I}.\frac{1+Cos(\beta)}{2} + r.\frac{1-Cos(\beta)}{2} \tag{6-13}$$

$$E_{PV} = P_{m,cor}.PSH.R \tag{6-14}$$

$$DE = E_{PV} - F.Q_{Lday} \tag{6-15}$$

$$SOC = SOCa + \frac{DE}{C_L.V} \tag{6-16}$$

$$E_{loss} = (SOC-1).C_L.V \tag{6-17}$$

$$SOC = SOCa - \frac{Q_{Lnight}.F'}{C_L.V} \tag{6-18}$$

Where

I_T is the intensity on the PV plane at the optimal angle of inclination

R is the conversion factor for the solar radiation from the horizontal to the inclined PV array

E_{PV} is the energy delivered by the PV (Wh)

$P_{m,cor}$ is the corrected Peak power of the PV (Wp)

PSH is the Peak Solar Hour

DE is the remaining amount of the energy delivered after its consumption by the loads

SOC is the state of charge of battery(%)

SOCa is the remaining SOC carried onto the subsequent hour

C_L is the battery capacity (Ah)

V is the DC transfer voltage

Q_{Lday},Q_{Lnight} are the hourly loads with the former denoting loads during the time the PV produces energy and the latter when the PV does not produce energy and the battery meets the loads

E_{loss} is the energy burnt by a damp load due to excess energy and fully charged battery (Wh)

Since the analysis is hourly,all the terms in the equations (6-12) to (6-18) denote hourly values.

6.4.1 Simulation Methodology

The hourly values of Global Solar Radiation intensity,I(W/m^2),Diffuse Solar Radiation Intensity,I_d(W/m^2), ambient temperature,T_a(^oC) are downloaded from a database(in this case Meteonorm) for all the days in December(November for Chennai).The Beam Solar Radiation Intensity,I_b(W/m^2) can then be calculated by means of equation (5-12) .

Next,the intensity on the inclined plane,I_T has to be determined . The optimal angle of inclination is that which gives the maximum output when considered on an yearly basis.This value for London was obtained from PVGIS and is 38^o .The intensity on the PV plane at this angle of inclination(I_T) is given by equation (6-12).

The installed peak power of the PV(P_m) is initially assumed to be 1 kW or the initial assumed value may also be calculated by equation (6-8) with d = 1.In our case,the value is initially assumed to be 1kW.The battery capacity ,C_L is calculated by means of equation 6-10 wherein the days of autonomy,d is considered to be unity and the load Q_L is the average daily load of the seasonal month with the maximum load.

The performance of the PV is simulated for the entire month for each hour in a platform (in this case MS - EXCEL)and the number of hours of failure i.e., the number of hours the state of charge of the Battery goes below (1-DOD)or in other words less than 20% is determined.For non-critical loads ,the percentage of failure as stated in section 6.3 has to be less than 5%.In this stochastic approach,the percentage of failure is calculated by dividing the number of hours in which the battery SOC goes below 20% by the total number of hours for the month of December which is 744 (31X24).

In case the failure is less than 5%,the peak power P_m is suitably altered until the failure is just below 5%.If the failure is more than 5%,the peak power of the P_m is increased in steps of 0.5kW and for each of this increase the battery capacity is proportionately increased from the original calculated value (with d=1).For instance if the peak power is doubled from the 1kW to 2kW,the battery capacity is also doubled .

For each of these instances, the failure rate for the total month is calculated and the analysis is continued until the selected value of peak power and the corresponding battery capacity produces a failure rate no more than 5% throughout the month.The Peak power may also be increased in steps of 0.25kW (or even smaller) and the battery capacity,C_L proportionately increased until the failure rate becomes no more than 5%.This final value of Peak Power,P_m and the Battery Capacity,C_L represent the sizing of the PV system.

Table 6-14 ,6-15 and 6-16 shows the values of energy produced by the PV(E_{PV}) , the delivered energy(DE),state of charge of the Battery(SOC), the energy burnt by a damp load(E_{loss}) etc., calculated for a typical day (n = 11) for different values of Peak Power (P_m) and Battery Capacity (C_L) for London.Tables IV-A and IV-B in Appendix IV shows the above mentioned entities for Patras and Chennai respectively during a typical day.

Table 6-14:PV Simulation values on a typical day(n=11) for Peak Power P_m = 1.5 kW and Battery Capacity ,C_L = 186Ah // London(December)

Hour	Ambient Temperature ,T_a(°C)	Global Solar Radiation Intensity,I (W/m^2)	Diffuse Solar Radiation Intensity,I_d(W/m^2)	Intensity on the inclined plane,I_T(W/m2)	Night based consumption profile fractions(PVGIS)	Hourly Load,(W)	Peak power corrected for temperature,(Wp)	Energy produced by PV,E_{PV}(Wh)	Delivered Energy, DE(Wh)	State of Charge of Battery,SOC(%)	Energy burnt,E_{loss}(Wh)
1	11.5	0	0	0	0.0505	92.415	1500	0	0	-1.30	0
2	11.5	0	0	0	0.035	64.05	1500	0	0	-3.17	0
3	11.3	0	0	0	0.027	49.41	1500	0	0	-4.61	0
4	10.6	0	0	0	0.025	45.75	1500	0	0	-5.94	0
5	9.5	0	0	0	0.0245	44.835	1500	0	0	-7.25	0
6	8.5	0	0	0	0.0265	48.495	1500	0	0	-8.66	0
7	9.3	0	0	0	0.0345	63.135	1500	0	0	-10.50	0
8	8.8	0	0	0	0.0295	53.985	1500	0	0	-12.08	0
9	8.5	29	26	73.82	0.023	42.09	1485.05	109.62	50.88	-10.94	0
10	9.4	124	72	368.77	0.018	32.94	1425.32	525.62	479.65	-0.18	0
11	10.1	161	88	400.37	0.018	32.94	1418.92	568.10	522.13	11.53	0
12	11.6	266	114	707.50	0.0205	37.515	1356.73	959.89	907.53	31.89	0
13	11.6	198	97	489.11	0.0265	48.495	1400.95	685.22	617.54	45.74	0
14	11.5	181	74	537.69	0.035	64.05	1391.12	747.99	658.60	60.51	0
15	11.2	111	44	431.55	0.0415	75.945	1412.61	609.61	503.63	71.81	0
16	10.2	23	23	20.56	0.0505	92.415	1495.84	30.76	-98.22	69.61	0
17	8.5	0	0	0	0.0455	83.265	1500	0	0	67.18	0
18	7.8	0	0	0	0.034	62.22	1500	0	0	65.37	0
19	7.1	0	0	0	0.025	45.75	1500	0	0	64.04	0
20	6.6	0	0	0	0.03	54.9	1500	0	0	62.44	0
21	6	0	0	0	0.065	118.95	1500	0	0	58.97	0
22	6.1	0	0	0	0.1095	200.39	1500	0	0	53.13	0
23	5.7	0	0	0	0.1175	215.03	1500	0	0	46.86	0
24	4.6	0	0	0	0.088	161.04	1500	0	0	42.17	0

The rate of failure for this instance of simulation (P_m = 1.5 kW,C_L=186Ah) was very high and found to be 84.94%(i.e.,698 hrs failure out of 744 hrs)

Note : A negative value of SOC implies that the state of charge of the Battery is zero .

Table 6-15 : PV Simulation values on a typical day(n=11) for Peak Power P_m = 2kW and Battery Capacity ,C_L = 236Ah // London(December)

Hour	Ambient Temperature ,T_a(^{o}C)	Global Solar Radiation Intensity,I (W/m^2)	Diffuse Solar Radiation Intensity,I_d(W/m^2)	Intensity on the inclined plane,I_T(W/m2)	Night based consumption profile fractions(PV GIS)	Hourly Load,(W)	Peak power corrected for temperature,(Wp)	Energy produced by PV,E_{PV}(Wh)	Delivered Energy, DE(Wh)	State of Charge of Battery,SOC(%)	Energy burnt,E_{loss}(Wh)
1	11.5	0	0	0	0.0505	92.415	2000	0	0	76.67	0
2	11.5	0	0	0	0.035	64.05	2000	0	0	75.27	0
3	11.3	0	0	0	0.027	49.41	2000	0	0	74.19	0
4	10.6	0	0	0	0.025	45.75	2000	0	0	73.19	0
5	9.5	0	0	0	0.0245	44.835	2000	0	0	72.21	0
6	8.5	0	0	0	0.0265	48.495	2000	0	0	71.15	0
7	9.3	0	0	0	0.0345	63.135	2000	0	0	69.77	0
8	8.8	0	0	0	0.0295	53.985	2000	0	0	68.59	0
9	8.5	29	26	73.82	0.023	42.09	1980.07	146.16	90.17	70.18	0
10	9.4	124	72	368.77	0.018	32.94	1900.43	700.83	657.01	81.78	0
11	10.1	161	88	400.37	0.018	32.94	1891.90	757.46	713.65	94.37	0
12	11.6	266	114	707.50	0.0205	37.515	1808.98	1279.85	1229.95	100.00	911.17
13	11.6	198	97	489.11	0.0265	48.495	1867.94	913.63	849.12	100.00	849.12
14	11.5	181	74	537.69	0.035	64.05	1854.82	997.31	912.12	100.00	912.12
15	11.2	111	44	431.55	0.0415	75.945	1883.48	812.82	711.80	100.00	711.80
16	10.2	23	23	20.56	0.0505	92.415	1994.45	41.01	-81.92	98.55	0
17	8.5	0	0	0	0.0455	83.265	2000	0	0	96.73	0
18	7.8	0	0	0	0.034	62.22	2000	0	0	95.37	0
19	7.1	0	0	0	0.025	45.75	2000	0	0	94.37	0
20	6.6	0	0	0	0.03	54.9	2000	0	0	93.17	0
21	6	0	0	0	0.065	118.95	2000	0	0	90.57	0
22	6.1	0	0	0	0.1095	200.39	2000	0	0	86.19	0
23	5.7	0	0	0	0.1175	215.03	2000	0	0	81.49	0
24	4.6	0	0	0	0.088	161.04	2000	0	0	77.97	0

The rate of failure for this instance of simulation (P_m = 2kW,C_L=236Ah) was 65.59% (i.e.,.496 hrs failure out of 744 hrs).

Table 6-16:PV Simulation values on a typical day(n=11) for Peak Power P_m = 4kW and Battery Capacity ,C_L = 495 Ah // London(December)

Hour	Ambient Temperature ,T_a(°C)	Global Solar Radiation Intensity,I (W/m^2)	Diffuse Solar Radiation Intensity,I_d(W/m^2)	Intensity on the inclined plane,I_T(W/m2)	Night based consumption profile fractions(PV GIS)	Hourly Load,(W)	Peak power corrected for temperature,(Wp)	Energy produced by PV,E_{PV}(Wh)	Delivered Energy, DE(Wh)	State of Charge of Battery,SOC(%)	Energy burnt,E_{loss}(Wh)
1	11.5	0	0	0	0.0505	92.415	4000	0	0	88.70	0
2	11.5	0	0	0	0.035	64.05	4000	0	0	88.00	0
3	11.3	0	0	0	0.027	49.41	4000	0	0	87.46	0
4	10.6	0	0	0	0.025	45.75	4000	0	0	86.96	0
5	9.5	0	0	0	0.0245	44.835	4000	0	0	86.47	0
6	8.5	0	0	0	0.0265	48.495	4000	0	0	85.94	0
7	9.3	0	0	0	0.0345	63.135	4000	0	0	85.25	0
8	8.8	0	0	0	0.0295	53.985	4000	0	0	84.66	0
9	8.5	29	26	73.82	0.023	42.09	3960.139	292.324	233.58	86.62	0
10	9.4	124	72	368.77	0.018	32.94	3800.862	1401.66	1355.7	98.03	0
11	10.1	161	88	400.37	0.018	32.94	3783.8	1514.92	1469	100.00	1234.52
12	11.6	266	114	707.50	0.0205	37.515	3617.951	2559.69	2507.3	100.00	2507.34
13	11.6	198	97	489.11	0.0265	48.495	3735.88	1827.26	1759.6	100.00	1759.58
14	11.5	181	74	537.69	0.035	64.05	3709.649	1994.63	1905.2	100.00	1905.24
15	11.2	111	44	431.55	0.0415	75.945	3766.962	1625.64	1519.7	100.00	1519.65
16	10.2	23	23	20.56	0.0505	92.415	3988.896	82.0202	-46.953	99.61	0
17	8.5	0	0	0	0.0455	83.265	4000	0	0	98.70	0
18	7.8	0	0	0	0.034	62.22	4000	0	0	98.02	0
19	7.1	0	0	0	0.025	45.75	4000	0	0	97.52	0
20	6.6	0	0	0	0.03	54.9	4000	0	0	96.92	0
21	6	0	0	0	0.065	118.95	4000	0	0	95.62	0
22	6.1	0	0	0	0.1095	200.39	4000	0	0	93.43	0
23	5.7	0	0	0	0.1175	215.03	4000	0	0	91.08	0
24	4.6	0	0	0	0.088	161.04	4000	0	0	89.32	0

The failure rate in this instance of simulation is 11.82%(i.e.,88 hrs failure out of 744 hrs) which is much lesser than the earlier 2 cases but still higher than the permissible limit of 5%.Finally, the failure rate was brought down to just less than 5% by increasing the Peak power of the PV in smaller steps and was determined to be 4110W i.e., 4.1kW with the corresponding Battery capacity,C_L as 508.97Ah which after applying the correction factor (as explained in section 6.3 of step 9) becomes 940.59Ah.As the peak power is increased with corresponding increase in battery capacity the failure rate goes down.Also it can be observed from all instances of simulation that for each increase of Peak power P_m ,the battery capacity C_L was also proportionately increased as explained earlier in the simulation methodology.

Chapter 7

COST EFFECTIVE CONFIGURATION FOR SOLAR COLLECTOR

In order to determine the fraction of thermal needs to be covered by the solar collector that is economically attractive, 8 scenarios as presented in Table 7-1 are considered in Patras. For each scenario the fraction of needs not met by the Solar Collector is achieved by the use of Heating Oil .The ideal fraction of needs is decided based on the Internal Rate of Return(IRR) and the Net Present value (NPV).

Table 7-1: Different fractions of thermal loads by solar collector

Scenario	% of Thermal loads met by Solar Collector(Space heating +Hot water + Heat Losses)	% of Thermal loads covered by Oil(Space heating +Hot water + Heat Losses)
1	30	70
2	40	60
3	50	50
4	60	40
5	70	30
6	80	20
7	90	10
8	100	0

Internal rate of return (IRR) is the interest rate at which the net present value of all the cash flows (both positive and negative) from a project or investment equal zero.The basic formula for calculating IRR is :

$$\boldsymbol{P_0 + \frac{P_1}{1+IRR} + \frac{P_2}{(1+IRR)^2} + \frac{P_3}{(1+IRR)^3} + \cdots \frac{P_n}{(1+IRR)^n} = 0} \qquad 7\text{-}1$$

where P_0, P_1, . . . P_n equals the cash flows in periods 1,2,….n, respectively and

IRR equals the project's internal rate of return.The higher the IRR,the more it becomes appealing for any situation.

Net Present Value (NPV) is defined as the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in capital budgeting to analyse the profitability of a projected investment of project.It is defined by the equation as given below :

$$\boldsymbol{NPV = -CI + \sum_{t=1}^{N} \frac{C_{in}}{(1+i)^n} - \sum \frac{C_{out}}{(1+i)^n}} \qquad \text{7-2}$$

Where

CI refers to the Capital investment cost

C_{in} refers to the cash inflows each year.

C_{out} refers to the cash outflows (maintenance etc.,)each year

i refers to the rate at which the cash flow is discounted each year

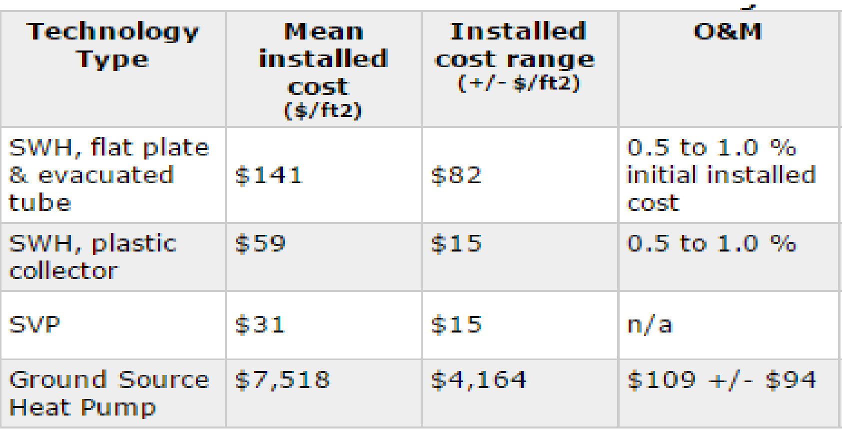
n refers to the number of years.

A positive Net present value(NPV) indicates that the projected earnings generated by a project or investment exceeds the anticipated costs.Generally an investment with a positive NPV will be profitable and one with a negative NPV will result in loss.This concept is the basis for the Net Present Value,which dictates that the only investments that should be made are those with positive NPV values.

To proceed with the economic analysis,it is important to have an idea about the capital costs required for the solar collector and the operations & Maintenance costs(O&M).To this end, the costs provided in Table 7-2 and Fig.7-1 which have been taken from NREL website can be used as the reference.

Table 7-2:Costs for Solar Thermal Technologies

(Source : NREL)



Technology Type	Mean installed cost ($/ft2)	Installed cost range (+/- $/ft2)	O&M
SWH, flat plate & evacuated tube	$141	$82	0.5 to 1.0 % initial installed cost
SWH, plastic collector	$59	$15	0.5 to 1.0 %
SVP	$31	$15	n/a
Ground Source Heat Pump	$7,518	$4,164	$109 +/- $94

From Table 7-2, it can be noticed that the mean installed cost per Flat pate solar collectors is \$141/ft^2 and the installed cost range is (+/- \$82/ft^2).For this analysis,the capital costs of the Flat Plate Solar Collectors has been assigned the lower range i.e., \$59/ft^2 (\$141/ft^2 - \$82/ft^2) . \$59/ft^2 is equivalent to 54.41€/ ft^2 (1\$ = 0.9222€ based on the exchange rate as on 17/12/2015 when this analysis was performed).The above figure on further conversion to SI units leads to a cost of 585.66 €/m^2 (1m^2 = 10.76ft^2) of flat plate collector.The Operations & Maintenance Cost (O&M) has been taken as 1% of the initial installed cost i.e., Capital Cost.

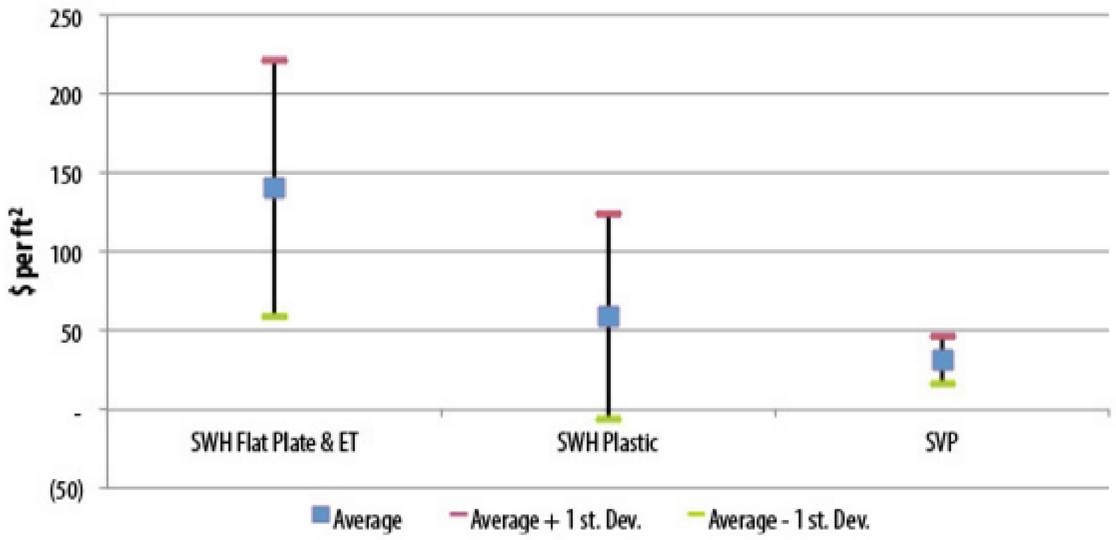


Figure 7-1: Installed Costs for Solar Thermal Technologies

(Source : NREL)

Table 7-3 shows the quantity of Heating Oil required in litres if it were used to satisfy 100% of the thermal energy demand(Space Heating + Hot Water + Heat Losses).This is obtained by dividing the total thermal energy demand by the calorific value of the Heating Oil.It is to be mentioned here that Heating Oil has a Net calorific value of 11.8kWh per litre(Source : Biomass Energy Centre).

Table 7-3: Oil Consumption in litres to cover 100%Thermal Loads

	London				Patras			
	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct
Total Thermal Loads as from Table 5-22	4872.61	3403.49	1136.29	2779.92	3291.88	1899.04	414.88	735.78

Heating Oil required in (litres)	412.93	288.43	96.30	235.59	278.97	160.94	35.16	62.35

The Net Present value(NPV) and the Internal Rate of Return(IRR) calculated for each scenario is presented in Table 7-4.The Flat Plate collector choosen for this analysis has an area of 2m^2 and the data is available for the cost of collector per m^2 (shown earlier). Hence accordingly,the capital cost per collector(area 2m^2) was computed as 1171.32€ .The solar collector output in Patras for January was calculated in the previous chapter in Table 6-3 as 154.05kWh Hence the minimum collector area required for each scenario was obtained by multiplying the corresponding fraction of thermal needs covered by solar collector with the thermal demand for the month of January and dividing the result by the Solar Collector output.Subsequently, since each collector has an area of 2m^2 , the number of collectors required for each scenario can be calculated.The capital cost for the collectors was calculated by multiplying the number of collectors with the cost of each collector i.e., 1171.32€.The Operations and Maintenance cost (1% of the capital cost) was computed for each case.

In all scenarios presented in Table 7-4,the fraction of needs(%) covered by the solar collector corresponds to an equivalent fraction of oil that can be saved in litres. For instance,if 40% of the needs are covered by Solar collector,it means that savings amount to 40% of the quantity of oil in litres.Multiplying this quantity of oil with the cost per litre of Oil amounts to savings in euros.Hence for each period of the year(Jan-Mar,Apr-Jun,Jul-Sep,Oct-Nov),the savings in litres of oil is calculated for the seasonal months i.e.,(Jan,Apr,Oct and Nov),multiplied with the cost of Heating Oil/litre for Patras (Source:European Commission) and the resulting value is multiplied by 3 to account for the 3 months in each period. This might not be the most accurate way to obtain the annual saving in litres of oil as the thermal load is different for each month. However, it can be used to determine the net annual savings quickly which is obtained after deducting the O&M Costs.

The Cash inflow for the year can be calculated by the sum of the cash in flows for each period.The net savings in euros can then be obtained by subtracting the cash outflow per year from the cash inflow per year.The NPV and the IRR were calculated by means of an Online Financial calculator .The rates at which the cash flows are discounted each year i.e., the interest rates was 0.75% for investment in Greece (Source : global- rates).

Table 7-4: NPV & IRR table for Solar Collector,Patras

				US$/ft^2	Euros/ft^2	US$/m^2	Euros/m^2	Cost per Flat Plate Collector (with area 2m^2)Euros				1171.32		
Cost of Collector				59	54.41	635.07	585.66							
Area per collector(m^2)				2										
Life Expectancy of the Collector				20 Years										
Scenario	% of Thermal loads met by Solar Collector(Space heating +Hot water + Heat Losses)	% of Thermal loads covered by Oil(Space heating +Hot water + Heat Losses)	Minimum Collector Area(m^2) required for Covering the Loads	No. of Collectors (Rounded off to nearest whole number)	Total capital cost on the collectors(***Capital Investment ,CI)***	Operations and Maintenance Cost(1% of capital cost)***(Cash Outflow/yr)***	Savings in euros,€ by using solar collector and avoiding Oil(Period)				Total savings in euros,€ for the year(***Cash inflow***)	Net Savings per year in euros,€(Cash inflow - Cash outflow)	Internal Rate of Return(% Per annum)	Net Present Value euros(NPV)
							Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec				
1	30	70	6	3	3754.49	37.54	203.37	117.32	25.63	45.46	391.78	354.24	6.99	2768.55
2	40	60	9	5	5856.62	58.57	271.16	156.43	34.17	60.61	522.37	463.81	4.85	2684.07
3	50	50	11	6	7027.94	70.28	338.95	195.54	42.72	75.76	652.97	582.69	5.40	3701.83
4	60	40	13	7	8199.26	81.99	406.74	234.64	51.26	90.91	783.56	701.57	5.78	4719.59
5	70	30	15	8	9370.59	93.71	474.53	273.75	59.81	106.06	914.15	820.45	6.05	5737.34
6	80	20	17	9	10011.97	100.12	542.32	312.86	68.35	121.22	1044.75	944.63	7.00	7382.63
7	90	10	19	10	11263.46	112.63	610.11	351.97	76.89	136.37	1175.34	1062.71	7.00	8305.49
8	100	0	21	11	12514.96	125.15	677.90	391.07	85.44	151.52	1305.94	1180.79	7.00	9228.34

From Table 7-4 ,it is evident that the best scenario is when 100% of the needs are covered by the Solar Collector.It has a Net present Value(NPV) of 9228.34 euros over the life time of the collector (20 years) which is higher than that for other scenarios.In addition,the Internal Rate of Return(IRR) is also amongst the highest with a value of 7%.Hence it can be concluded that for Patras,Solar collectors for covering the thermal needs (Space Heating + Hot Water + Heat Losses) is a very good option.

The procedure discussed in this chapter is repeated for the solar collector in London and the results are shown in Table 7-5.For calculation of NPV,the rate at which the cash flows were discounted was 0.5% .It can be seen from Table 7-5 that all the scenarios yield in a negative value of NPV and a negative IRR.Only 3 scenarios are presented for the city of London as it became clear that increasing the fraction of thermal needs covered by the solar collector only resulted in the NPV becoming more negative which is clearly an unfavourable option. Hence it can be concluded that for the building in London,satisfying the thermal needs by a solar collector does not look economically feasible.Hence other options like Heat Pump may be explored.

Table 7-7: NPV & IRR table for Solar Collector, London

	US$/ft^2	Euros/ft^2	US$/m^2	Euros/m^2	Cost per Flat Plate Collector (with area 2m^2)Euros	1171.32
Cost of Collector	59	54.41	635.07	585.66		
Area per collector(m^2)	2					
Life Expectancy of the Collector	20 Years					

Scenario	% of Thermal loads met by Solar Collector(Space heating +Hot water + Heat Losses)	% of Thermal loads covered by Oil(Space heating +Hot water + Heat Losses)	Minimum Collector Area(m^2) required for Covering the Loads	No. of Collectors (Rounded off to nearest whole number)	Total capital cost on the collectors(***Capital Investment ,CI)***	Operations and Maintenance Cost(1% of capital cost)***(Cash Outflow/yr)***	Savings in euros,€ by using solar collector and avoiding Oil(Period)				Total savings in euros,€ for the year(***Cash inflow***)	Net Savings per year in euros,€(Cash inflow - Cash outflow)	Internal Rate of Return(% Per annum)	Net Present Value(NPV)
							Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec				
1	20	80	23	12	14055.88	140.56	128.09	89.47	29.87	73.08	320.51	179.95	(negative)	-10639.09
2	30	70	34	17	19808.20	198.08	192.14	134.21	44.81	109.62	480.77	282.69		-14440.7
3	40	60	45	23	26940.44	269.40	256.18	178.94	59.74	146.16	641.03	371.62		-19884.3

Chapter 8

RESULTS AND DISCUSSIONS

8.1 Comparison of Space Heating Load between the 2 approaches

The procedure explained in section 5.4.2 (Space Heating Load calculation by using hourly temperature data) is repeated for the other seasonal months of London , continued for Patras and the results are tabulated and compared with the space Heating Loads calculated in section 5.4.1 using the average monthly ambient temperature .

Table 8-1: Space heating Load using 2 approaches (*comparison*)

S.NO	Approach	Load	London				Patras			
			Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct
1	Monthly Ambient Temperature from RetScreen	Heating (kWh)	4396.7	3284.9	1045.9	2535.4	3053.6	1837.2	0	858.317
2	Hourly Temperature data ± 3 days representative day		4180.5	4013.3	1083.9	2786.4	2470.6	1626.5	0	555.3

As noticed from Table 8-1,the space heating loads calculated from both the approaches match more or less with considerable difference in April for London and in January for Patras (greater than 500 kwh in both cases) .

In April for London, the space Heating load calculated from the second approach is much higher than that of the first approach.This is because the hourly temperature values(Refer Table III-A, Appendix III for hourly values) on the 7 days considered is lower than the monthly ambient temperature for April (9.5^{o}C) as used in the first approach.This explains why the space Heating load is higher in the second approach .The exact opposite case exists for Patras in January i.e., the hourly temperature values exceed the monthly ambient temperature(10^{o}C) in many hours(Refer Table III-B ,Appendix III for hourly values) .

Hence coming to the question of which approach to adopt during calculation of space Heating Load in general,the second approach (i.e., calculated using hourly values of ambient temperature ± 3 days representative day)takes preference over the other approach because the hourly values represent a more accurate picture although the second approach is more time consuming and extensive .However ,it is to be mentioned that in this thesis, the values calculated using the first approach has been adopted .

8.2 Comparison of the sizing of stand-alone PV between the 2 approaches

The simulation approach described in section 6.4 is repeated for the other cities(Patras and Chennai) and the results obtained are tabulated and compared with the results of the approach in section 6.3 henceforth described as classical .

Table 8-2:Comparison of PV sizing details - Classic and Stochastic approaches

S.No	Approach	London		Patras		Chennai	
		Peak Power of PV,P_m (kW)	Corrected Battery Capacity,C_L (Ah)	Peak Power of PV,P_m (kW)	Battery Capacity, C_L(Ah)	Peak Power of PV,P_m (kW)	Battery Capacity,C_L (Ah)
1	Classic	8.8	2400	3.8	1000	2.19	600
2	Stochastic	4.11	940.59	1.95	451.57	1.27	372.38
	% Decrease in capacity over classic approach	-53.29	-60.81	-48.68	-54.84	-42.01	-37.94

As seen from Table 8-2,the stochastic approach results in much lower PV peak power and installed Battery capacity compared to the classical approach which tends to oversize the system depending on the autonomy factor.The percentage decrease in the installed peak power of the PV is more than 40% for all the cities which can lead to substantial savings in money.There is also a considerable decrease in the battery capacity which in turn means less money invested in the case of the stochastic approach compared to the classical approach.

Hence for sizing of stand-alone PV systems ,the stochastic approach although involving extensive and voluminous analysis (data comprising each hour for an entire month) is much better as it leads to reduction in the Peak power,P_m of the PV and the Battery Capacity ,C_L by a considerable percentage with the loss of load probability(LLP) still under the 5% margin.

Chapter 9

CONCLUSIONS

In order to convert an existing building into a Zero Energy Building, it is important to reduce the energy demand of the building to a minimal before using Renewables.This is achieved by the use of passive solar techniques wherein by means of the incoming solar radiation through the windows the load of space Heating is reduced.

- A single storey Building was considered in 3 cities .In order to convert the building into a ZEB, the overall thermal Heat Losses coefficient for the building $(UA)_b$ was calculated initially.This value can be suitably reduced (if it does not pertain to the region’s local building regulations)by the use of proper insulation.

- The building loads comprising Thermal (Space Heating + Domestic Hot Water + Heat Losses) and the Electric loads was determined in each of the cities for the seasonal months. The thermal energy demand for the building (Space Heating in London and Patras) was reduced by factoring the Solar Gain through the Windows.Also a comparison was made between the 2 approaches used to calculate Space Heating Load and the 2 approaches used for sizing of stand-alone PV with discussion on the better approach for each case.

- A solar collector was selected to satisfy the thermal loads (Heating for London & Patras) and for Chennai a Heat Pump was choosen to meet the cooling Load.It was observed that 100% of the needs can be covered by Solar Collector in Patras with very good Net Present Value(NPV) and Internal rate of Return(IRR).However, in London the outcome with Solar Collectors was not so good and the thermal needs can be satisfied by other means such as a Heat Pump.

APPENDICES

Appendix – I

Table I-A : Global(G) and Diffuse Solar Radiation(G_d) in W/m^2 on representative day of Seasonal months for Chennai

(Source : PVGIS CM-SAF)

Local Solar Time	Jan		Apr		July		Oct	
	G	G_d	G	G_d	G	G_d	G	G_d
06:07	-	-	46	38	74	65	-	-
06:22	-	-	87	60	111	91	-	-
06:37	58	46	136	80	150	115	80	64
06:52	101	66	189	98	191	136	120	86
07:07	149	85	244	114	231	156	163	106
07:22	200	102	301	129	270	174	206	125
07:37	251	117	358	142	309	190	249	141
07:52	303	131	414	153	346	204	292	156
08:07	353	142	469	163	381	216	333	168
08:22	402	153	522	171	415	227	372	179
08:37	448	162	573	178	446	236	409	188
08:52	492	169	621	183	475	243	444	196
09:07	533	175	666	188	502	249	477	202
09:22	572	181	708	191	527	254	507	207
09:37	607	185	747	194	550	258	534	212
09:52	639	188	782	195	570	261	559	215
10:07	667	191	813	197	587	263	581	217
10:22	692	192	841	197	603	264	600	219
10:37	714	194	865	198	616	265	617	220
10:52	732	195	885	198	627	266	630	221
11:07	747	196	901	198	635	266	641	221
11:22	757	196	913	198	642	267	649	222
11:37	765	196	921	198	646	267	655	222
11:52	768	197	925	198	648	267	657	222
12:07	768	197	925	198	648	267	657	222
12:22	765	196	921	198	646	267	655	222
12:37	757	196	913	198	642	267	649	222
12:52	747	196	901	198	635	266	641	221
13:07	732	195	885	198	627	266	630	221
13:22	714	194	865	198	616	265	617	220
13:37	692	192	841	197	603	264	600	219
13:52	667	191	813	197	587	263	581	217

14:07	639	188	782	195	570	261	559	215
14:22	607	185	747	194	550	258	534	212
14:37	572	181	708	191	527	254	507	207
14:52	533	175	666	188	502	249	477	202
15:07	492	169	621	183	475	243	444	196
15:22	448	162	573	178	446	236	409	188
15:37	402	153	522	171	415	227	372	179
15:52	353	142	469	163	381	216	333	168
16:07	303	131	414	153	346	204	292	156
16:22	251	117	358	142	309	190	249	141
16:37	200	102	301	129	270	174	206	125
16:52	149	85	244	114	231	156	163	106
17:07	101	66	189	98	191	136	120	86
17:22	58	46	136	80	150	115	80	64
17:37	24	24	87	60	111	91	44	40
17:52	-	-	46	38	74	65	-	-
18:07	-	-	15	15	40	38	-	-

Table I - B :Global(G) and Diffuse Solar Radiation(G_d) in W/m^2 on representative day of Seasonal months for London

(Source : Climate -SAF PVGIS)

Local Solar Time	Jan		Apr		July		Oct	
	G	G_d	G	G_d	G	G_d	G	G_d
04:22	-	-	-	-	30	30	-	-
04:37	-	-	-	-	49	46	-	-
04:52	-	-	-	-	69	61	-	-
05:07	-	-	-	-	91	76	-	-
05:22	-	-	-	-	114	91	-	-
05:37	-	-	50	45	138	106	-	-
05:52	-	-	73	60	163	119	-	-
06:07	-	-	97	74	188	133	-	-
06:22	-	-	122	88	214	145	-	-
06:37	-	-	149	101	239	157	-	-
06:52	-	-	175	113	264	168	-	-
07:07	-	-	202	125	289	178	39	36
07:22	-	-	228	135	314	187	57	49
07:37	-	-	254	145	337	196	76	61
07:52	-	-	279	154	360	204	95	72
08:07	-	-	303	162	382	211	115	82
08:22	35	32	326	169	403	217	134	92

08:37	46	39	348	175	422	222	152	101
08:52	57	46	369	181	441	227	170	109
09:07	68	52	388	186	458	231	186	116
09:22	78	58	406	190	474	235	202	122
09:37	88	63	422	193	489	238	216	127
09:52	96	67	437	196	502	241	229	132
10:07	104	71	451	199	514	243	241	137
10:22	111	74	462	201	524	245	251	140
10:37	117	77	472	203	533	246	260	143
10:52	123	80	481	204	540	247	268	146
11:07	127	82	487	205	546	248	274	148
11:22	130	83	492	206	550	249	278	149
11:37	132	84	496	207	553	249	281	150
11:52	133	84	497	207	555	249	283	150
12:07	133	84	497	207	555	249	283	150
12:22	132	84	496	207	553	249	281	150
12:37	130	83	492	206	550	249	278	149
12:52	127	82	487	205	546	248	274	148
13:07	123	80	481	204	540	247	268	146
13:22	117	77	472	203	533	246	260	143
13:37	111	74	462	201	524	245	251	140
13:52	104	71	451	199	514	243	241	137
14:07	96	67	437	196	502	241	229	132
14:22	88	63	422	193	489	238	216	127
14:37	78	58	406	190	474	235	202	122
14:52	68	52	388	186	458	231	186	116
15:07	57	46	369	181	441	227	170	109
15:22	46	39	348	175	422	222	152	101
15:37	35	32	326	169	403	217	134	92
15:52	25	23	303	162	382	211	115	82
16:07	-	-	279	154	360	204	95	72
16:22	-	-	254	145	337	196	76	61
16:37	-	-	228	135	314	187	57	49
16:52	-	-	202	125	289	178	39	36
17:07	-	-	175	113	264	168	22	22
17:22	-	-	149	101	239	157	-	-
17:37	-	-	122	88	214	145	-	-
17:52	-	-	97	74	188	133	-	-
18:07	-	-	73	60	163	119	-	-
18:22	-	-	50	45	138	106	-	-
18:37	-	-	29	29	114	91	-	-
18:52	-	-	-	-	91	76	-	-
19:07	-	-	-	-	69	61	-	-
19:22	-	-	-	-	49	46	-	-

19:37	-	-	-	-	31	30	-	-
19:52	-	-	-	-	14	14	-	-

Table I-C :Global(G) and Diffuse Solar Radiation(G_d) in W/m^2 on representative day of Seasonal months for Patras

(Source : Climate -SAF PVGIS)

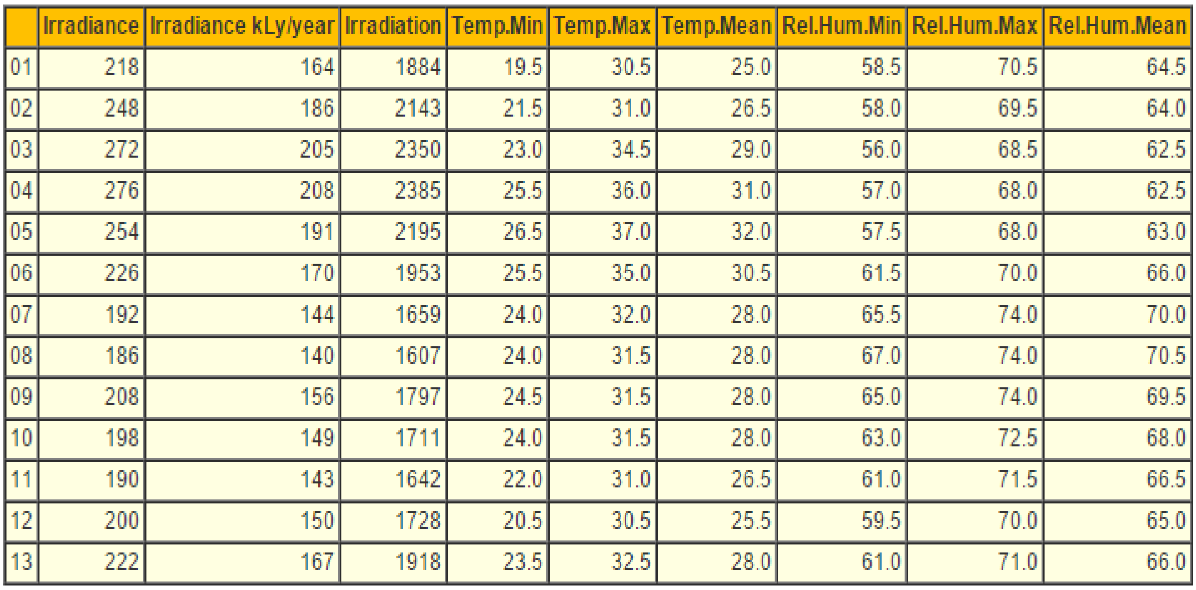
Local Solar Time	Jan		Apr		July		Oct	
	G	G_d	G	G_d	G	G_d	G	G_d
05:07	-	-	-	-	28	28	-	-
05:22	-	-	-	-	54	47	-	-
05:37	-	-	-	-	83	65	-	-
05:52	-	-	41	41	115	82	-	-
06:07	-	-	74	62	149	99	-	-
06:22	-	-	104	81	186	115	-	-
06:37	-	-	137	99	225	129	-	-
06:52	-	-	171	115	264	143	39	39
07:07	-	-	206	131	304	156	57	57
07:22	-	-	240	145	344	167	97	73
07:37	38	38	274	158	383	178	126	88
07:52	62	52	308	169	422	187	155	101
08:07	82	65	341	180	460	196	184	114
08:22	102	76	372	189	497	203	212	125
08:37	122	87	402	197	532	210	240	135
08:52	141	96	430	204	565	216	266	144
09:07	159	105	456	210	596	221	291	152
09:22	176	113	481	215	626	225	314	159
09:37	192	119	503	220	652	229	336	165
09:52	206	125	524	223	677	232	356	170
10:07	220	130	542	226	699	234	373	174
10:22	231	135	558	229	718	236	389	178
10:37	241	138	572	230	735	237	403	181
10:52	250	141	583	232	749	239	414	184
11:07	256	143	592	233	761	240	423	185
11:22	262	145	599	234	769	240	430	187
11:37	265	146	604	234	775	241	434	188
11:52	267	147	606	235	778	241	437	188
12:07	267	147	606	235	778	241	437	188
12:22	265	146	604	234	775	241	434	188
12:37	262	145	599	234	769	240	430	187
12:52	256	143	592	233	761	240	423	185
13:07	250	141	583	232	749	239	414	184

13:22	241	138	572	230	735	237	403	181
13:37	231	135	558	229	718	236	389	178
13:52	220	130	542	226	699	234	373	174
14:07	206	125	524	223	677	232	356	170
14:22	192	119	503	220	652	229	336	165
14:37	176	113	481	215	626	225	314	159
14:52	159	105	456	210	596	221	291	152
15:07	141	96	430	204	565	216	266	144
15:22	122	87	402	197	532	210	240	135
15:37	102	76	372	189	497	203	212	125
15:52	82	65	341	180	460	196	184	114
16:07	62	52	308	169	422	187	155	101
16:22	42	38	274	158	383	178	126	88
16:37	24	23	240	145	344	167	97	73
16:52	-	-	206	131	304	156	70	57
17:07	-	-	171	115	264	143	44	39
17:22	-	-	137	99	225	129	22	21
17:37	-	-	104	81	186	115	35	32
17:52	-	-	74	62	149	99	19	19
18:07	-	-	46	41	115	82	-	-
18:22	-	-	21	20	83	65	-	-
18:37	-	-	89	72	54	47	-	-
18:52	-	-	68	58	30	28	-	-
19:07	-	-	47	43	8	8	-	-

Appendix – II

Table II – A : Monthly means of Irradiances ,Temperature and Humidity,Chennai

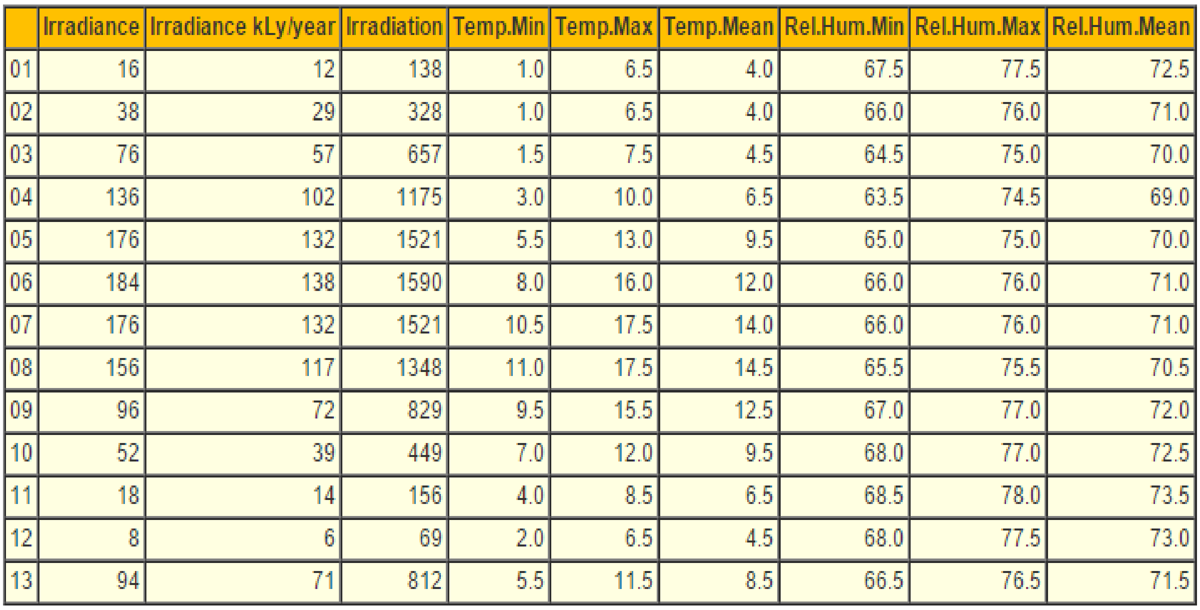
(Source : SoDa)



	Irradiance	Irradiance kLy/year	Irradiation	Temp.Min	Temp.Max	Temp.Mean	Rel.Hum.Min	Rel.Hum.Max	Rel.Hum.Mean
01	218	164	1884	19.5	30.5	25.0	58.5	70.5	64.5
02	248	186	2143	21.5	31.0	26.5	58.0	69.5	64.0
03	272	205	2350	23.0	34.5	29.0	56.0	68.5	62.5
04	276	208	2385	25.5	36.0	31.0	57.0	68.0	62.5
05	254	191	2195	26.5	37.0	32.0	57.5	68.0	63.0
06	226	170	1953	25.5	35.0	30.5	61.5	70.0	66.0
07	192	144	1659	24.0	32.0	28.0	65.5	74.0	70.0
08	186	140	1607	24.0	31.5	28.0	67.0	74.0	70.5
09	208	156	1797	24.5	31.5	28.0	65.0	74.0	69.5
10	198	149	1711	24.0	31.5	28.0	63.0	72.5	68.0
11	190	143	1642	22.0	31.0	26.5	61.0	71.5	66.5
12	200	150	1728	20.5	30.5	25.5	59.5	70.0	65.0
13	222	167	1918	23.5	32.5	28.0	61.0	71.0	66.0

Table II – B : Monthly means of Irradiances ,Temperature and Humidity,London

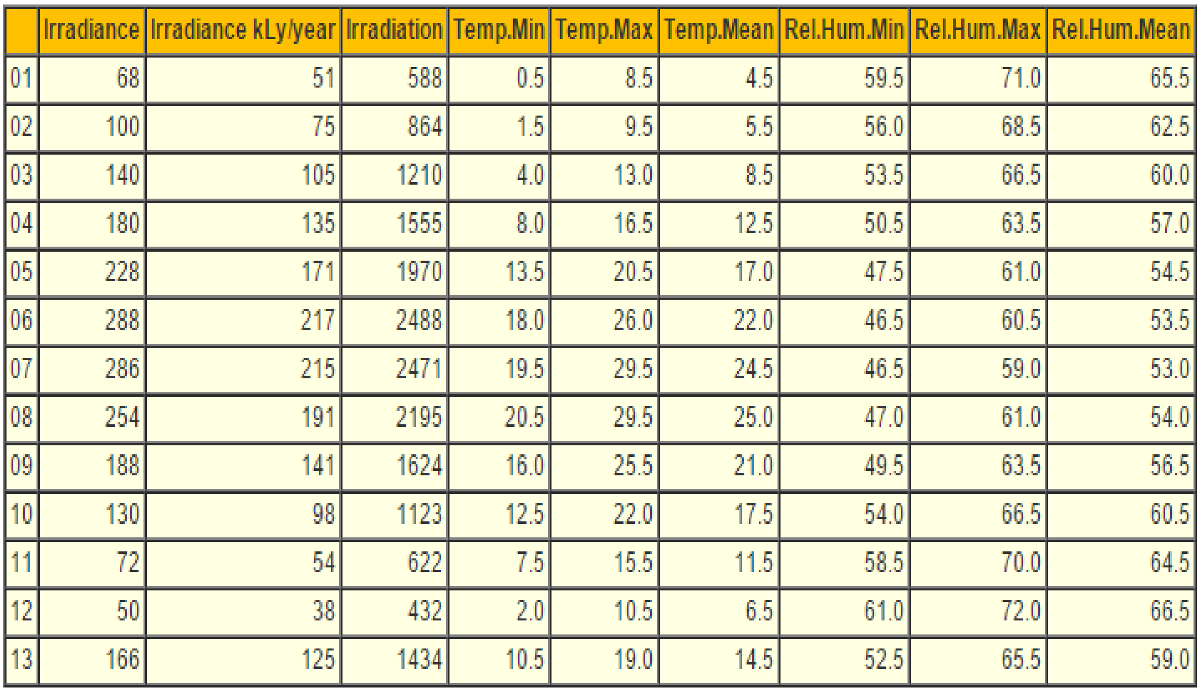
(Source : SoDa)



	Irradiance	Irradiance kLy/year	Irradiation	Temp.Min	Temp.Max	Temp.Mean	Rel.Hum.Min	Rel.Hum.Max	Rel.Hum.Mean
01	16	12	138	1.0	6.5	4.0	67.5	77.5	72.5
02	38	29	328	1.0	6.5	4.0	66.0	76.0	71.0
03	76	57	657	1.5	7.5	4.5	64.5	75.0	70.0
04	136	102	1175	3.0	10.0	6.5	63.5	74.5	69.0
05	176	132	1521	5.5	13.0	9.5	65.0	75.0	70.0
06	184	138	1590	8.0	16.0	12.0	66.0	76.0	71.0
07	176	132	1521	10.5	17.5	14.0	66.0	76.0	71.0
08	156	117	1348	11.0	17.5	14.5	65.5	75.5	70.5
09	96	72	829	9.5	15.5	12.5	67.0	77.0	72.0
10	52	39	449	7.0	12.0	9.5	68.0	77.0	72.5
11	18	14	156	4.0	8.5	6.5	68.5	78.0	73.5
12	8	6	69	2.0	6.5	4.5	68.0	77.5	73.0
13	94	71	812	5.5	11.5	8.5	66.5	76.5	71.5

Table II – C :Monthly means of Irradiances ,Temperature and Humidity,Patras

(Source : SoDa)



	Irradiance	Irradiance kLy/year	Irradiation	Temp.Min	Temp.Max	Temp.Mean	Rel.Hum.Min	Rel.Hum.Max	Rel.Hum.Mean
01	68	51	588	0.5	8.5	4.5	59.5	71.0	65.5
02	100	75	864	1.5	9.5	5.5	56.0	68.5	62.5
03	140	105	1210	4.0	13.0	8.5	53.5	66.5	60.0
04	180	135	1555	8.0	16.5	12.5	50.5	63.5	57.0
05	228	171	1970	13.5	20.5	17.0	47.5	61.0	54.5
06	288	217	2488	18.0	26.0	22.0	46.5	60.5	53.5
07	286	215	2471	19.5	29.5	24.5	46.5	59.0	53.0
08	254	191	2195	20.5	29.5	25.0	47.0	61.0	54.0
09	188	141	1624	16.0	25.5	21.0	49.5	63.5	56.5
10	130	98	1123	12.5	22.0	17.5	54.0	66.5	60.5
11	72	54	622	7.5	15.5	11.5	58.5	70.0	64.5
12	50	38	432	2.0	10.5	6.5	61.0	72.0	66.5
13	166	125	1434	10.5	19.0	14.5	52.5	65.5	59.0

Appendix – III

Table III – A : Hourly Temperature values ± 3 days representative day for London,April

(Source : Meteonorm)

Hour	Ref Temp(°C)	Hourly Temperature (°C)						
		12th day	13th day	14th day	15th day	16th day	17th day	18th day
1	22	8	6.4	4.8	4	4.3	2.7	4.4
2	22	8	5.6	4.5	3.7	4.2	2.7	4
3	22	7.5	5.3	4.8	3.8	4.2	2.6	4.3
4	22	7.1	5.3	4.4	3.5	4.3	2.7	4.6
5	22	7.2	4.9	4.6	3.6	3.8	2.5	4.8
6	22	7.7	4.9	5.1	3.2	5.1	3.7	5.8
7	22	8.1	5	5.1	4.4	5.4	4.1	6
8	22	9.2	5.5	5.2	5.4	5.8	4.7	6.9
9	22	9.8	6.2	4.8	5.4	6.3	5.6	8
10	22	10.5	7	4.6	6	7.4	6.6	8.6
11	22	11.4	7.4	4.5	6	8.3	7.5	9.6
12	22	12.2	7	5.5	6.6	9.3	8.2	10.7
13	22	12.8	6.8	5.9	7.3	10.4	9	12.2
14	22	12.9	6	6.1	7.4	10.7	8.8	12.2
15	22	12.9	6	6.3	7.6	10.9	9.1	11.7
16	22	12.4	6.2	6.4	7.7	10.7	9.5	11.9
17	22	12.3	6.3	6.2	8.2	9.7	9	11.7
18	22	10.8	6.3	6.3	7.2	8.6	8	10.4
19	22	10.5	5.7	5.3	7.3	6.8	8	9.9
20	22	9.4	6.3	5	6.5	5.7	7.7	8.9
21	22	8.8	6.8	5.1	5.4	5.5	6.4	8
22	22	7.7	5.9	4.6	4.9	4.6	5.3	7.3
23	22	6.4	5.4	4.6	4.6	3.8	5.6	6.3
24	22	6.8	4.6	4	4.4	2.4	5	6.4

Table III – B :Hourly Temperature values ± 3 days representative day for Patras,January

(Source : Meteonorm)

Hour	Ref Temp(°C)	Hourly Temperature (°C)						
		14th day	15th day	16th day	17th day	18th day	19th day	20th day
1	22	8.5	11.2	14	11.9	10.1	10.4	11.7
2	22	8.5	12.2	14.5	11.7	10	10.3	11.2
3	22	8	11.8	14.2	12.1	9.8	10.9	11.2
4	22	8.3	11.1	15	12.2	9.2	11.1	11.9
5	22	8.6	11.1	14.5	11.8	8.8	11	11
6	22	8.8	12.1	13.8	11	8.6	10.6	10.7
7	22	8.6	12.4	14.1	11.4	8.5	9.8	10.9
8	22	9.4	13.1	14.6	11.4	8.2	10	11.3
9	22	9.5	13.7	15.3	10.7	8.5	10.6	11.5
10	22	9.2	13.9	15.2	11.3	9.2	11.1	11.3
11	22	9.6	13.8	15.5	11	9.9	11.7	11.8
12	22	10.1	14.9	15.9	10.1	10.7	13.3	12.1
13	22	10.6	14.6	17.5	9.6	12.2	14.2	13.1
14	22	11.3	15.3	19.4	9.8	13.1	15.4	13.7
15	22	11.8	14.8	19.9	10.9	13.9	16.7	14.9
16	22	11.7	14.5	20.4	11	13.9	16.7	15.5
17	22	12.3	14.7	19.5	10.5	13.2	16.6	15.8
18	22	11.8	14.9	18	10.4	12.9	14.7	14.4
19	22	12.1	14.7	16.5	10	11.8	14	12.8
20	22	12	14.6	15.4	10.4	11.5	13.4	12.2
21	22	12.2	14.1	14.3	9.8	11.9	12.2	12.3
22	22	11.6	13.8	13.3	10.3	11.7	11.6	11.4
23	22	12.1	14.3	12.8	10.5	10.8	11.8	10.9
24	22	12	14	12.6	9.9	10.6	12	11.3

Appendix – IV

Table IV-A:PV Simulation values on a typical day(n=11) for Peak Power P_m = 1.96 kW and Battery Capacity ,C_L = 342.1Ah // Patras (December)

Hour	Ambient Temperature,T_a(^{o}C)	Global Solar Radiation Intensity ,I(W/m^2)	Diffuse Solar Radiation Intensity ,I_d(W/m^2)	Intensity on the inclined plane,I_T(W/m2)	Night based consumption profile fractions (PVGIS)	Hourly Load,(W)	Peak power corrected for temperature,(Wp)	Energy produced by PV,E_{PV}(Wh)	Delivered Energy,DE(Wh)	State of Charge of Battery,SOC(%)	Energy burnt,E_{loss}(Wh)
1	10.6	0	0	0	0.0505	137.36	1950	0	0	52.90	0
2	11.3	0	0	0	0.035	95.2	1950	0	0	51.46	0
3	11.5	0	0	0	0.027	73.44	1950	0	0	50.36	0
4	11.6	0	0	0	0.025	68	1950	0	0	49.33	0
5	11.5	0	0	0	0.0245	66.64	1950	0	0	48.33	0
6	10.7	0	0	0	0.0265	72.08	1950	0	0	47.24	0
7	10.8	0	0	0	0.0345	93.84	1950	0	0	45.82	0
8	11.6	0	0	0	0.0295	80.24	1950	0	0	44.61	0
9	12.3	90	52	187.296	0.023	62.56	1900.69	355.993	272.777	47.93	0
10	13.2	209	77	427.415	0.018	48.96	1837.48	785.368	720.243	56.71	0
11	13.9	299	135	514.986	0.018	48.96	1814.43	934.406	869.281	67.29	0
12	14.4	420	140	763.849	0.0205	55.76	1748.92	1335.91	1261.74	82.66	0
13	14.8	383	194	607.072	0.0265	72.08	1790.19	1086.77	990.895	94.73	0
14	15.8	413	139	780.836	0.035	95.2	1744.44	1362.13	1235.49	100.00	802.81
15	15.6	356	76	826.35	0.0415	112.88	1732.46	1431.62	1281.47	100.00	1281.5
16	15.2	206	93	500.299	0.0505	137.36	1818.3	909.693	726.98	100.00	726.98
17	15.3	80	46	557.795	0.0455	123.76	1803.16	1005.79	841.172	100.00	841.17
18	14.1	0	0	0	0.034	92.48	1950	0	0	98.61	0
19	13.3	0	0	0	0.025	68	1950	0	0	97.58	0
20	12.4	0	0	0	0.03	81.6	1950	0	0	96.35	0
21	12.1	0	0	0	0.065	176.8	1950	0	0	93.68	0
22	12	0	0	0	0.1095	297.84	1950	0	0	89.19	0
23	11.7	0	0	0	0.1175	319.6	1950	0	0	84.37	0
24	11.8	0	0	0	0.088	239.36	1950	0	0	80.76	0

The rate of failure for this instance of simulation is 4.70 %(i.e., 35 hrs failure out of 744 hrs throughout the month of December)

Table IV-B: PV Simulation values on a typical day(n=15) for Peak Power P_m = 1.2 kW and Battery Capacity ,C_L = 285.6 Ah //Chennai (November)

Hour	Ambient Temperature,T_a (^oC)	Global Solar Radiation Intensity,I (W/m^2)	Diffuse Solar Radiation Intensity, I_d(W/m^2)	Intensity on the inclined plane,I_T(W/m2)	Night based consumption profile fractions (PVGIS)	Hourly Load,(W)	Peak power corrected for temperature,(Wp)	Energy produced by PV,E_{PV}(Wh)	Delivered Energy,DE(Wh)	State of Charge of Battery,SOC(%)	Energy burnt, E_{loss}(Wh)
1	25.3	0	0	0	0.0505	186.345	1200	0	0	10.91	0
2	25.4	0	0	0	0.035	129.15	1200	0	0	8.58	0
3	25.3	0	0	0	0.027	99.63	1200	0	0	6.78	0
4	24.9	0	0	0	0.025	92.25	1200	0	0	5.11	0
5	24.7	0	0	0	0.0245	90.405	1200	0	0	3.48	0
6	24.8	0	0	0	0.0265	97.785	1200	0	0	1.71	0
7	24.6	26	26	25.557	0.0345	127.305	1195.86	30.56	-138.775	-0.31	0
8	25.1	73	73	71.756	0.0295	108.855	1188.38	85.27	-59.5224	-1.18	0
9	26.1	264	226	273.563	0.023	84.87	1155.68	316.15	203.26	1.78	0
10	27.9	567	308	631.242	0.018	66.42	1097.74	692.94	604.589	10.60	0
11	29.3	810	224	941.434	0.018	66.42	1047.49	986.14	897.79	23.70	0
12	29.6	729	384	796.844	0.0205	75.645	1070.91	853.35	752.729	34.68	0
13	30.6	440	375	447.626	0.0265	97.785	1127.48	504.69	374.621	40.15	0
14	31.6	503	376	525.906	0.035	129.15	1114.8	586.28	414.49	46.19	0
15	31.6	314	288	316.069	0.0415	153.135	1148.8	363.10	159.403	48.52	0
16	30.5	184	180	182.345	0.0505	186.345	1170.46	213.43	-34.4431	48.02	0
17	29.4	76	76	74.705	0.0455	167.895	1187.9	88.74	-134.587	46.05	0
18	28	10	10	9.830	0.034	125.46	1198.41	11.78	-155.103	43.79	0
19	27.5	0	0	0	0.025	92.25	1200	0	0	42.12	0
20	26	0	0	0	0.03	110.7	1200	0	0	40.12	0
21	26.6	0	0	0	0.065	239.85	1200	0	0	35.79	0
22	25.7	0	0	0	0.1095	404.055	1200	0	0	28.49	0
23	24.8	0	0	0	0.1175	433.575	1200	0	0	20.66	0
24	25.1	0	0	0	0.088	324.72	1200	0	0	14.79	0

The rate of failure for this instance of simulation is 13.75%(i.e., 99 hrs failure out of 720 hrs throughout the month of November)

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