CHAPTER 1 INTRODUCTION

To improve the thermal comfort conditions, particularly in the summer season, there is growing demand of conventional vapour compression air conditioners. This growing demand not only increases electricity consumption but also contributes to increase in global warming. Building architectural characteristics and trends like increasing proportion of transparent to opaque surfaces, use of less and low thermal walls, reduced ventilation have also significantly increased the use of air conditioners.

The conventional vapour compression refrigeration cycle driven air conditioner using grid electricity, increases the consumption of electricity and fossil energy. Energy sources based on fossil fuels such as coal, oil, gas, nuclear, etc., are cause serious environmental hazards and are scarce in nature, location and volume. One of the major environmental issues is acid rain resulting from sulphurous gases emitting from power plants, killing some sensitive living species, disrupting complex soil chemistry and affecting human health. Green house gases such as CO_2 (by product of combustion of fossil fuels), CH_4, N_2O, and halocarbons released from human activities absorb outgoing energy from the earth and cause warming effects. Additionally, the refrigerants used in air conditioners like chlorofluocarbures (CFCs), hydrochlorofluorocarbures (HCFCs) and hydrofluocarbues (HFCs) are also responsible for ozone depletion and global warming [Fan et al. 2007]. UN Intergovernmental Panel on Climate Change (IPCC) warned that average global temperature may increase by 1.4-4.5 K until 2100. Already the average global temperature has risen by 0.6 K in the last century. In view of seriousness of the situation, Kyoto Protocol was adopted in 1997, a legally binding agreement under which the industrialized countries will reduce their collective green house gases by 5.2% compared to the year 1990. In Europe HFC-134a was banned for the air conditioning units in the new cars started from 1 January 2009 [Kim et al. 2008].

In India phase out of HCFCs has been accelerated as per the decision taken at the 19th Meeting to the Montreal Protocol held in September 2007 at Montreal. Accordingly, a Roadmap was developed describing the long term vision and action plan including the policy instruments for phasing out of production and consumption of HCFCs. The overall objective of the Roadmap is to reduce production and consumption of HCFCs in various applications. Identification of enterprises in the refrigeration sector and assessment of equipment which are based on the HCFC technology needs to convert to non Ozone Depleting Substances (ODS) technologies has been scheduled since January 2013. The phase out of HCFCs are scheduled as 10% reduction in 2015, 35% reduction in 2020, 67.5% reduction in 2025 and 100% reduction in 2030 [Ministry of Environment and Forests India 2009].

Due to global warming, increased energy demand, limited resources and environmental pollution there is dire need for development of such technologies that can offer reduction in energy consumption, peak electrical demand, energy costs without lowering the desired level of comfort. These benefits relate to the reduction of energy consumption which can also significantly reduce the emission of CO_2 because buildings use around 50% of the total energy consumption in developed countries [Lombard et al. 2008]. Therefore, any analysis of building HVAC system that can effectively reduce this consumption is highly valuable. Although the words cooling, refrigeration and air conditioning carry different meanings, in this work they are used in similar context, practically carrying same meaning.

1.1. Solar Cooling Systems

Depleting fossils fuel resources, global warming and harmful emissions rise have renewed interest in renewable, alternative and abundant non-conventional sources of energy such as solar, wind, hydro, biomass, etc. out of these solar energy is a source of energy that cannot be exhausted. The power from the sun received by the earth is approximately $1.8 X 10^{11}$ MW which is greater than the present consumption rate on the earth. Thus, solar energy can supply all the present and future energy needs of the world. It has two important factors in its favour. First, it is a clean source of energy, and second, it is free and almost available in every part of the world where people live [Bajpai 2012]. In addition to the above advantages, solar energy for cooling is more attractive due to the reason that the demand of cooling is greatest when the availability of solar energy is abundant and cooling is more needed in the hotter climate than in colder climate. However, with the advantages there are some limitations also. Firstly, availability of radiation flux is low in many places that require large collecting areas in many applications. Secondly, intensity of radiation varies with time over the day-night cycle in a year. Due to the requirement of collection and storage of solar energy, it requires excessive initial cost.

Solar cooling is broadly classified in two ways, i.e., active and passive cooling. Most commonly used vapour refrigeration system which includes vapour compression and vapour absorption system comes in the family of active system. In the active system energy is used for cooling and coolant is circulating to transfer heat from one place to another. Passive solar cooling system is based on evaporative and radiative cooling process and can be integrated with building structures itself. These systems use natural processes and techniques of heat dissipation without the use of energy or insignificant amount of energy.

Fig. 1.1 gives an overview of various options to convert the solar radiation into cooling effect, mainly classifying in two ways: electric process (photovoltaic panel) and thermal process (solar thermal collector).

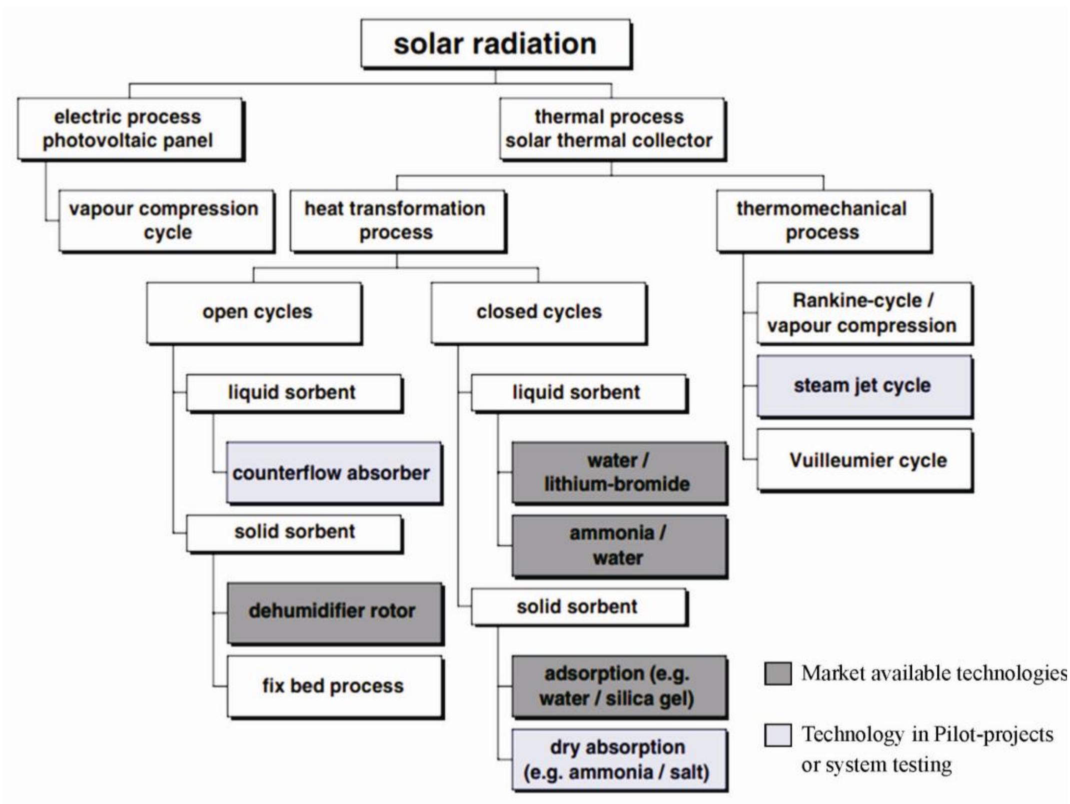


Fig. 1.1 Overview of physical conversion of solar radiation into cooling [Henning 2007].

1.1.1 Solar thermal cooling systems

In place of the use of electricity in conventional cooling systems, solar thermal cooling systems use solar heat to produce refrigerating effect. In such systems the phenomenon of sorption: the process by absorption liquid-gas and the process by adsorption solid gas, is utilized to produce the refrigeration effect.

Absorption based cooling systems

In the vapour absorption systems, a pair of substances having the strong affinity to form a solution is utilized. Among the pair of substances, the substance having lower boiling temperature is called refrigerant and the other is called absorbent. Fig. 1.2 shows a schematic of vapour absorption system in which mixture of refrigerant and absorbent is used to replace the mechanical compression by thermo compression through generator absorber assembly. Solar thermal collector is used to supply low grade heat input in the generator. Cooling is produced in the evaporator and heat is rejected from the condenser and the absorber.

The two major working pairs used in the solar absorption refrigeration systems are H_2O-LiBr and NH_3-H_2O. In the water lithium bromide pair water works as the refrigerant and other is the absorbent while in the ammonia water pair ammonia works as the refrigerant and water is the absorbent. H_2O-LiBr pair is mostly used in the air conditioning system having advantage over the NH_3-H_2O pair. It has high COP and low operation pressures; it is non-toxic, environmental-friendly and has large latent heat of vaporization. On the other hand, water works as the refrigerant so it is not suitable for low temperature cooling and the risk of crystallization of LiBr solution requires anti-crystallization device. Broadly speaking, NH_3-H_2O systems are often used for refrigeration purpose while H_2O-LiBr systems are more suitable for air conditioning purpose. Majority of vapour absorption systems are single effect with the solar flat-plate collectors at low temperatures. Recent research shows that there are also double effect and triple effect systems in the market having higher COP but they require high generator temperature (Fan et al. 2007).

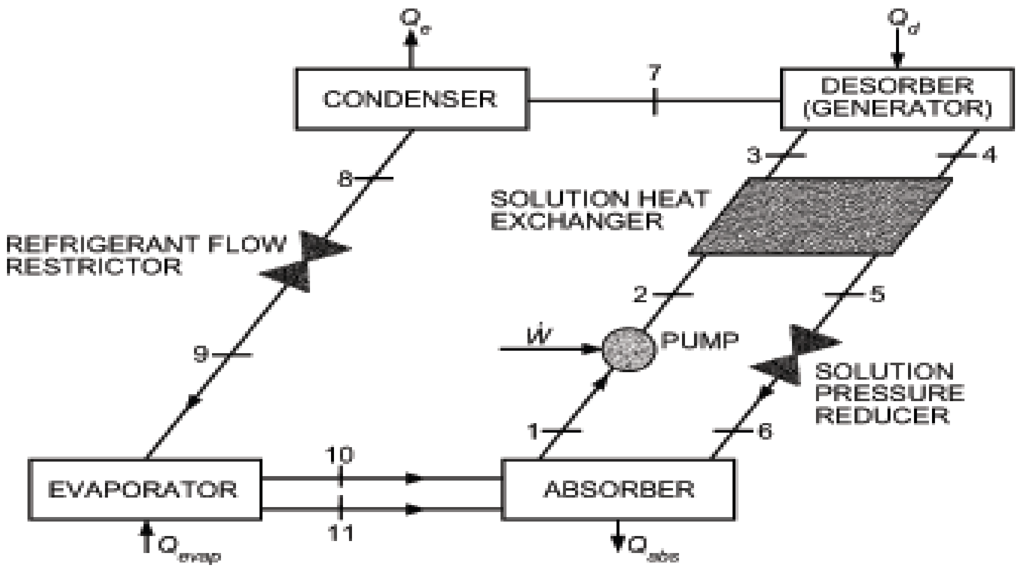


Fig. 1.2 Schematic of vapour absorption system (ASHRAE Fundamental 1997)

The average COP over a long term can be evaluated as [Duffi and Backman 2006]

$$COP = \frac{\int Q_E \, dt}{\int Q_G \, dt} \tag{1.1}$$

Currently, various absorption machines with COPs ranging from 0.3 to 1.2 are available. For double-effect LiBr-water chillers with COPs around 1.2 are available for air conditioning which use solar collector capable of working at 150°C but the costs of these systems are high. So less expensive collectors working at around 90°C, single effect LiBr-water absorption machine with a COP between 0.6 and 0.8 are commonly preferred over double effects systems.

Adsorption based cooling systems

In absorption based cooling system the sorbent materials are liquids. Beside these some solid sorption materials are also available. The process of refrigeration in which solid sorbents are used is called adsorption refrigeration. In these cycles, typically a quasi continuous operation requires at least two compartments which contain the adsorption material are operated in parallel (Fig. 1.3). Activated carbon, silica gel and zeolite are most widely used adsorbents while water, methanol (ethanol) or ammonia are most widely used refrigerants in solar powered refrigerator. They consist of basically two sorbent compartments, the evaporator and the condenser.

While the sorbent in the first compartment is regenerated using external heat source, the sorbent in the second compartment (adsorber) adsorb the water vapour coming out from the evaporator. The water in the evaporator is transferred into the gas phase being heated from the external water cycle; here actually the useful cooling is produced [Henning 2007].

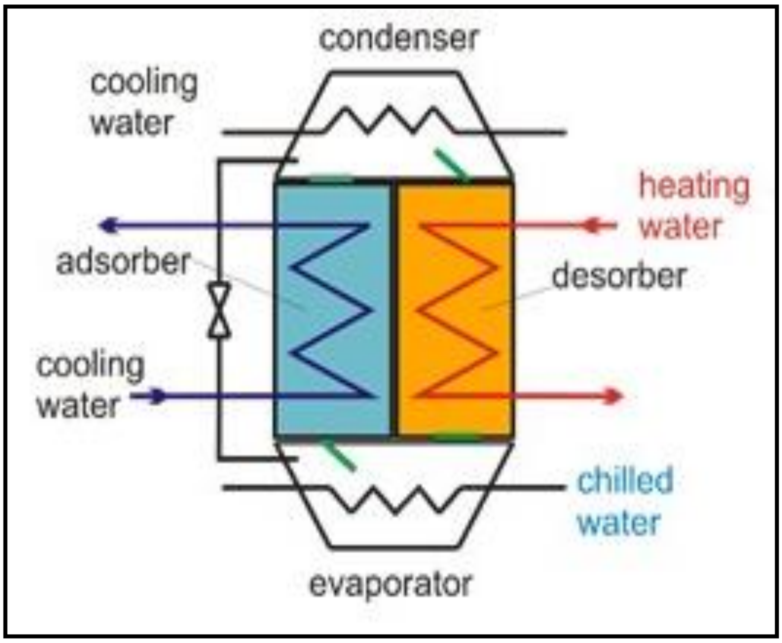


Fig. 1.3 Schematic diagram of the adsorption refrigerator [Henning 2007]

The organic refrigerant and ammonia have the advantage of being compatible with copper tubing system, low cost and low operating pressures. Under typical operating conditions with a temperature of the driving heat of about 80°C, the system achieves a COP of about 0.6. A very few manufactures produce adsorption chillers.

Desiccant cooling systems

Thermally driven chillers produce chilled water which can be supplied to any type of air conditioning equipment. Open sorption cooling is more commonly called desiccant cooling which produces directly conditioned air. Various desiccants are available in liquid or solid phases like silica gel, activated alumina, zeolite, LiCl and LiBr. In a liquid desiccant cooling system, the liquid desiccant circulates between an absorber and a regenerator in the same manner as in an absorption system. Main difference is that the equilibrium temperature of a liquid desiccant is determined not by the total pressure but by the partial pressure of water in the humid air to which the solution is exposed to.

Advantage and disadvantage of solar thermal based cooling systems

Absorption, adsorption and desiccant cooling system based on solar energy have some advantage and disadvantage relative to each other. Table 1.1 show the advantage and disadvantage of solar thermal cooling systems

Table 1.1 Advantage and disadvantage of solar thermal cooling systems

Absorption	Adsorption	Desiccant
Advantage: 1. High COP 2. Mature technology commercial products are available in markets Disadvantage : 1. Complicated 2. Moving parts	Advantage: 1. Low heat application can be driven as low as 50 °C temperature 2. High storage capacity and energy densification 3. No moving parts Disadvantage : 1. Require high vacuum pressures 2. Large volume and weight of the system 3. Low COP 4. Two or more unit required for continuous cooling	Advantage: 1. Independent control of latent loads in the ventilated air 2. Eliminates the condensation on cooling coils 3. Lower humidity level in occupied space provides the equivalent comfort level at high ambient temperature. 4. Reduced the mechanical cooling loads Disadvantage : 1. High initial cost 2. Increased maintenance cost of the aided desiccant equipment

1.1.2 Solar electric cooling systems

A solar electric refrigeration system consists mainly of photovoltaic panels and an electric refrigeration device based on vapor compression system. Photovoltaic panels consist of solar cells which are basically made of semiconductor materials that convert the incident solar radiation into direct current. This direct current may be directly used to drive the DC compressor or may be converted into

AC to drive the conventionally used AC compressor. Using solar panels for refrigeration has many advantages. They are simple, compact in size, high power to weight ratio and have no moving parts. Fig1.4 shows the schematic of solar electric vapour compression based system in which solar panel drive the DC motor of the compressor for producing the cooling effect in the evaporator by absorbing heat and rejecting heat to the ambient by the condenser.

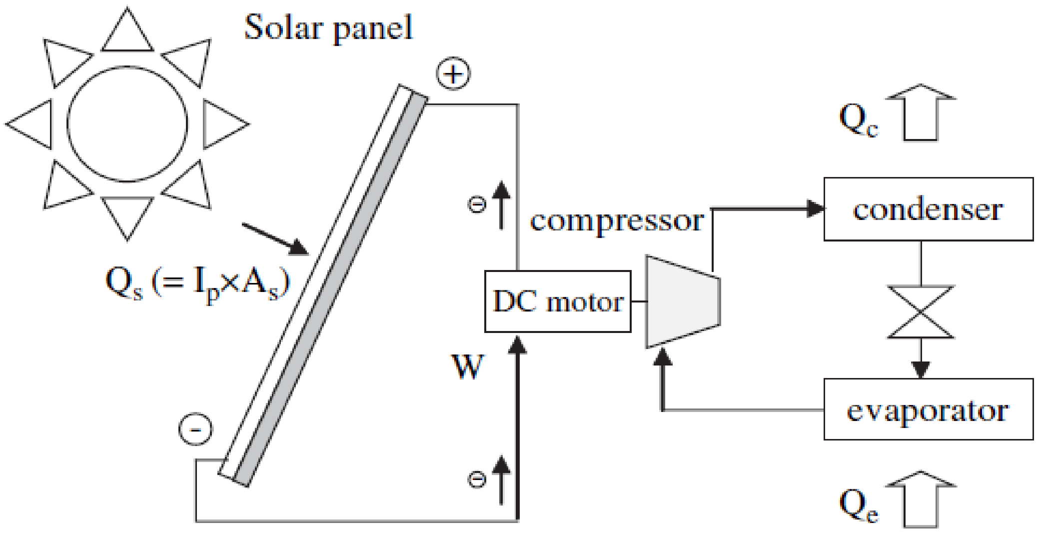


Fig. 1.4 Schematic diagram of solar electric compression cooling system [Kim et al. 2008]

The efficiency of solar panel is given by

$$\eta_{sol-pow} = \frac{W}{I_p X A_s} = \frac{W}{Q_s} \quad (1.2)$$

The refrigeration machine efficiency is defined as the ratio of cooling effect to the work input

$$\eta_{pow-cool} = \frac{Q_e}{W} \quad (1.3)$$

Overall efficiency of solar electric cooling system is given by combination of Eq. (1) and Eq. (2)

$$\eta_{sol-cool} = \eta_{sol-pow} X \, \eta_{pow-cool} = \frac{Q_e}{Q_s} \quad (1.4)$$

Solar electric vapour compression systems are not very widely used so far but recently some commercial products have hit the market, mainly in developed countries. There are several challenges in the broader commercial utilization of this type of systems. Firstly, the system should be supported by some means of storage with varying electricity production rate with time, e.g., batteries, mixed use of solar and grid. Secondly, the price of solar photovoltaic panel is high and efficiency is low. If a 10% efficiency solar photovoltaic panel is combined with a vapour compression air conditioner with 3.0 COP, the overall efficiency will be 30% [Kim et al.2008].

Based on the use of power sources the solar electric cooling system may be classified as Stand alone, Grid supported and Net metering system.

Stand alone PV cooling system

In the stand alone PV cooling system the cooling device is wholly operated by the power generated from PV. These systems are not connected by the grid power.

Grid supported PV cooling system

The grid supported PV cooling system is operated by the power generated from the photovoltaic panels and if the energy demand by the air conditioner is higher than the generated by the PV remaining power is taken from the public grid. If the power generated by the PV is higher than the required by the air conditioner surplus power is dumped.

Net metering system

Net metering is a concept where an instrument which has an exclusive metering and billing contract between utilities and their consumers, facilitates the connection of small, renewable energy-generating systems to the power grid. When a net metering client’s renewable energy generator is producing more power than is being consumed, the electric meter runs backward generating credits. Whenever the net metering customer uses more power than is being produced, the meter runs forward normally. Net metering customers are charged only for the net power that they consume from the electricity service provider and with this arrangement customers ensures the always have a reliable source of energy [MNRE 2012]. In the net metering based cooling system considered in this study, the air conditioner is operated by the power from the PV and if the power demanded by the air conditioner is higher than generated by PV, remaining power is taken from the grid. If the power generated by the PV is higher than the power demanded by the air conditioner than the surplus power is fed to the public grid. Net metering customers are charged only for the net power that they consume from the electricity service provider.

1.2 Solar Cooling System: Application, Problems and Prospects

According to the temperature application solar cooling technologies are classified into three categories: (i) air conditioning (8-15°C) for spaces, (ii) refrigeration (0-8°C) for food and vaccine storage, (iii) and freezing (<0°C) for ice making or congelation purposes [Fan et al. 2007].

Over past few years, technical and economical challenges have limited the emergence of solar cooling technologies in the market to a significant extent. In the vapor absorption system it requires a solution pump and a rectifier for the vapour leaving the generator that introduce complications in the system design. Other problems with absorption and adsorption system are the expansion of the absorbent upon the absorption of the refrigerant and its low thermal conductivity. In most cases the cost of units is several times the conventional technology due to this reason several companies which produce SPV powered refrigerator have been forced to stop the production [Enibe 1997].

In spite of the problems solar cooling technologies can play a significant role in meeting the needs of people in the rural areas of the developing countries. If solar based refrigeration techniques are used in such areas it will not only save human life by preserving life saving medicines but also help in protecting the environmental. Various solar absorption air conditioners are installed in the world so far based on sorption cooling system that offers reduction in energy consumption and global warming. As the production of solar cooling units and cost of conventional energy sources increases in future these systems will become more and more economically viable.

1.3 Origin of the Problem

Review of available literature suggested the need to study solar cooling system because

1. In the developing countries a large proportion of the population lives in the remote areas where electricity is either not available or have long power cuts as a result storage of food and life saving medicines is not possible.
2. A large proportion of fossil fuel based energy sources which are limited are consumed to meet people's comfortable lives in space cooling and air conditioning. The conventional air conditioning is attained by vapour compression refrigeration using electric power which has a serious aggravation on the grid electricity load.
3. Depletion of the ozone layer by Chlorofluorocarbons (CFCs) poses serious harm to the environment which also results in thinking for some active and passive cooling method.
4. Techno economic comparison is required for small scale solar cooling units so that a policy measure for promoting any particular technology can be identified.

1.4 Scope of Present Research

Through exhaustive study of the available literature (presented in next chapter), following potential areas of study were identified:

- There are very few studies for solar photovoltaic air conditioning systems.
- Solar photovoltaic cooling systems working through different types of PV cell technologies such as poly or thin film cells are not studied so far.
- There are very few studies that compared the solar thermal and solar photovoltaic cooling systems coupled with building load. For Indian climate, comparison of solar thermal and photovoltaic cooling system is not studied.

In the present research, the above identified areas have been addressed. Year round hourly performance analysis of solar thermal and photovoltaic cooling system using TRANSOL and TRNSYS program respectively has been carried out for air conditioning of day-time operated office building.

Parametric study and performance analysis of solar thermal and photovoltaic cooling system has been performed considering the annual solar fraction, primary energy savings and electrical (grid) COP. In the solar thermal cooling system, three types of collectors (FPC, ETC and CPC) with variance of collector area ranging from 70 m^2-110 m^2 has been considered. Similarly, the same area of photovoltaic panel has been taken for the solar photovoltaic cooling with three types of panels (mono crystalline, poly crystalline and thin film). Analysis has been carried out for one representative city of each of the four climatic zones considered in this study. Ahmedabad represents hot and dry climate, Bangalore represents moderate climate, Chennai represents warm and humid climate and Delhi represents composite climate.

In this work the analysis of solar photovoltaic cooling system is carried out in two scenarios i.e. grid supported and net metering provision. In the net metering provision it is assumed that the electricity purchase and selling price are same. Solar photovoltaic cooling system with battery storage is not analysed because initial analysis shows that the capital cost of storage system is very high and it is also linked with annual maintenance cost. System also requires reoccurring cost at every 4-5 year for replacement of batteries. In this thesis whenever solar photovoltaic cooling system is mentioned it should be treated as grid supported.

Financial viability of the solar thermal and photovoltaic cooling system has been examined through comparison with the energy consumption of conventional (non-solar) cooling system for producing the same cooling effect. Payback period and internal rate of return are calculated for both the cooling systems. In order to see the effect of variation in investment cost, electricity rate etc. on payback period, sensitivity analysis is also carried out to robustness of results.

In the last in order to increase the solar fraction of the PV cooling system various techniques were analysed using tracking, thermal mass, modifying sizing approach of air conditioner and use of VRF technology.

1.5 Outline of the Thesis

This thesis is arranged in seven chapters. First chapter gives a basic introduction of the research work. Chapter 2 covers the literature review regarding solar thermal and solar electric (Photovoltaic) cooling systems for refrigeration and air conditioning applications. Chapter 3 is related to methodology and plan of research work. It also contains description of various components of solar cooling systems, description of simulation tools and description of building used in this study. Chapter 4 covers the modeling of solar thermal cooling system, analysis of cooling load of the building; model validation with the previous published work and covers the performance evaluation of solar thermal cooling system based on simulation results. Chapters 5 describe the performance evaluation of solar photovoltaic cooling system based on simulation results. Chapter 6 shows the technical and economical comparison of two technologies based on PV and thermal routes. Chapter7 is related to the analysis of various techniques that can ehance the solar fraction in operation of PV cooling system. In this chapter modeling and simulation results for tracking system, thermal mass, modifying air conditioning system sizing approach and use of VRF technology have been presented. The last chapter comprises of results, discussions and conclusions drawn from the study and future scope of work in this area.

CHAPTER- 2: LITERATURE REVIEW

Solar refrigeration engages a system where solar power is used for cooling purposes. It can provide clean energy for cooling and refrigeration applications all over the world. Solar energy is more attractive for cooling because it is in sync with the cooling demand particularly in the summer month. Various solar refrigeration technologies have been investigated in past and some are even developed to commercial level. This chapter deals with the literature regarding solar thermal and solar electric (photovoltaic) cooling systems.

2.1 Studies on Solar Thermal Cooling Systems

The solar thermal cooling system converts energy content of solar energy into cooling effect through heating effect of warm fluid. The existing system for producing cooling using solar thermal energy is based mainly on the phenomenon of sorption: the process by absorption liquid -gas and the process by adsorption solid-gas. The phenomenon of absorption is the mixture of a gas in a liquid, the two fluids presenting a strong affinity, to form a solution. This process is reversible. Adsorption is the general phenomenon resulting from the interaction between a solid (adsorbent) and a gas (refrigerant), based on a physical or chemical reaction process. In general the main difference between absorption and adsorption are located in the nature of the sorbent and the duration of the sorption cycle, which is significantly longer for adsorption [Fan et al. 2007].

2.1.1 Solar vapour absorption system studies

The first continuous absorption cooling machine using ammonia-water solution was built by Mignon and Rouart and was shown at the London Exhibition in 1862. In the early phase of the absorption refrigeration technology kerosene/ steam/heat or low grade energy sources were used. Since then numerous improvement have taken place in the initial design. Many researchers have developed solar assisted absorption refrigeration systems. Most of them have been produced as experimental units and computer codes were also written to simulate the systems [Kaushik 1989]. The literature review regarding the solar vapour absorption system can be grouped into the modeling and simulation studies and experimental studies.

Modeling and simulation studies

Saman et al. 1996 presented modelling of small capacity lithium bromide water absorption chiller operated by solar energy in Texas. The analysis was based on the first law of thermodynamics with LiBr as absorbent and H_2O as refrigerant. Results indicated that the system is capable of performing with COP values of up to 0.8 for generator temperature in the range of 80-95°C. The chiller can save approximately 3500 kWh/yr for a two ton unit and it will reduce emissions by 19 lb of NO_X, 5800 lb of CO_2 and 16 lb of SO_X per year.

Bell et al. 1996 performed a thermodynamic analysis of the absorption cooling cycle and studied the effect of various operating conditions on the thermal performance. The results of the thermodynamic analysis indicate that there are optimum values of generator temperature that give the maximum COP for each set of operating conditions. A satisfactory value of COP about 0.74 at a low generator temperature (68°C) can be achieved if the condenser and absorber temperature was kept 32°C.

Ghaddar et al. 1997 presented modeling and performance evaluation of a solar operated absorption cycle for all possible climate condition of Beirut. The result showed that the optimal water storage tank capacity of 1000 to 1500 liter is required to operate solely on solar energy for about seven hours a day with a minimum collector area of 23.3 m^2 for each ton of refrigeration. They found that the optimal performance of solar absorption system was attained at a tank volume to collector area ratio of 13 to 19 l/m^2 which leads to a solar fraction of 20-26%. If the solar energy is combined with domestic water heating, the absorption system will be marginally competitive than the conventional vapour compression system. Further improvements in the solar technology and escalation of fuel costs provide the favorable condition towards the use of solar energy.

Chih Wu et al. 1997 presented a mathematical optimization of solar absorption refrigerator. Real solar refrigerator usually operate between two limits maximum COP and maximum cooling load. Their model provided a basis for designing a real solar absorption refrigerator. It was found that such systems are economically sound when the same collector is used for both space heating and cooling and particularly advantageous in regions of the world where a shortage of installed electric power exists.

Chen et al. 1999 carried out thermodynamic analysis of a new type of absorption cycle which was co-driven both by solar energy and electricity. A compressor was in the absorption cycle. The cycle could overcome some major shortcoming of the traditional absorption refrigeration cycle that uses an unsteady heat sources like solar energy system. The developed cycle provided the steady refrigeration capacity, a lower heat load of the condenser, and also a higher value of COP equal to 1.6.

Florides et al. 2002 (a) presented a modeling simulation of absorption solar cooling system for Cyprus. The system was modeled with the TRNSYS simulation program for air conditioning of a typical house in Cyprus. The final optimum system consist of 15m^2 compound parabolic collector (CPC) tilted at 30 °C from the horizontal and a 600 liter hot water storage tank. It was found that system operates with maximum performance when the auxiliary boiler thermostat is set at 87°C. They concluded that the system requires 84,240 MJ annually for cooling and hot water production, out of that 41263 MJ are supplied by the solar energy. The life cycle saving of a complete system increases to C£ 1600 with an assumption that the cost of electricity is C£ 0.053 per kWh and the annual rate of increase is 4.9% per year.

Florides et al. 2002 (b) presented the modeling, simulation and total equivalent warming impact (TEWI) of a domestic-size absorption solar cooling system of 11 kW cooling capacity. Experimentally obtained heat and mass transfer coefficients were employed in the design and costing of system. The final optimum system consists of 15 m^2 compound parabolic collector with 600 liter hot water storage tank. The total life cycle cost of a complete system, comprising the collector and the absorption units of an order of C£ 13,380 for a life time of 20 years. They suggested that the system is economically competitive compared to conventional system if its capital cost is below C£ 2000 rather than the present cost of C£ 4800. The total equivalent warming impact (TEWI) of a conventional air conditioner is 1.2 times greater than that of the absorption cooling system.

Florides et al. 2003 further presented the characteristics and performance of a single stage lithium bromide (LiBr)–water absorption machine. The performance calculation carried out using computer program based on mathematical equation describing the properties of working fluid. Results show that as the absorber inlet LiBr percentage is increased the system COP gets decreased and pump mass flow rate also increases for a particular exit percentage ratio of LiBr. The cost for a nominal 10 kW unit that can cover the needs of a typical insulated house was estimated to be C£ 4300. The total cost of an absorption unit together with all necessary secondary devices and installation cost is estimated as C£ 4800.

Balghouthi et al. 2005 presented a solution to reduce environmental pollution and global warming in Tunisia by suggesting the solar power air conditioning in place of conventional vapour compression air conditioning systems. Simulation was carried out by using TRNSYS program for 10kW cooling system in order to optimize the various factors affecting the performance of the system. The final optimized system have the solar collector area of 30 m^2 with orientation due south at slope of 35°.

Assilzdeh et al. 2005 carried out the modeling and simulation of absorption solar cooling system with TRNSYS program. In this paper a 3.5 kW (one ton refrigeration) system was simulated by using a typical metrological year file containing the weather parameters for Malaysia. The optimized system consisted of 35 m^2 evacuated tubes solar collector tilted at 20°. They suggested that in order to achieve the continuous operation of the generator and increase in the reliability of the system, a hot water storage tank is essential for high quality performance.

Mazloumi et al. 2008 simulated a solar lithium bromide –water absorption cooling system with a parabolic trough collector for the climatically condition of Ahwaz. The system is designed to cool a typical house having the maximum cooling load of 17.5 kW. The results show that the minimum collector area of about 59.8 m^2 was required for the collector mass flow rate of 1800 kg/h with an initial temperature of the storage tank equal to the ambient temperature. The collector mass flow rate has negligible effects on the optimal capacity of the minimum required collector area but it has a significant effect on the optimal capacity of the storage tank.

Mateus et al. 2009 performed the energy and economic analysis of an integrated solar absorption cooling and heating system in three different location and climates. An office building, a hotel and a single family house were used for analysis and it was found that with the present energy cost the solar integrated system is not justifiable in any location using economical consideration only. Annual solar fraction is achieved 20-60% and compared to the flat plate collectors, vacuum tube collectors allow a reduction in collector area between 15 and 50 %.

Eicker et al. 2009 designed the solar thermal absorption chiller system for office building. Performance and economics of solar thermal absorption cooling system was analyzed and found that to achieve a given solar fraction of the total heat demand requires largely different collector surface and storage volumes, depending on the characteristics of the building load file and the chosen system technology and control strategy. For buildings located at Madrid, 80% solar fraction is possible for aperture areas between 2 and 4 m^2/kW cooling power, the high values occurring for larger full load hours. For each MWh of cooling energy demand collector area between 1.6 and 3.5 m^2 are required for the Spanish site and between 4.6 and 6.2 m^2 for the Stuttgart installation.

Alili et al. 2010 studied the feasibility of a solar powered absorption cycle under Abu Dhabi's conditions. They proposed a solar driven air conditioning system using evacuated tube collectors to drive 10 kW_c ammonia –water absorption chiller. Based on simulation result and thermal analysis the solar air conditioner system has a specific collector area of $6m^2/kW_c$ and a specific tank volume of 0.1 m^3 $/kW_c$. The selected system size requires about 47% less electrical energy than the widely spread vapour compression cycles of the same cooling capacity.

Hang et al. 2010 has explored the impact of hot and cold storages on the energy performance of the solar absorption cooling system for a benchmark medium sizes office building located at Los Angeles and California. The solar collector area of 200 m^2 was taken to provide the 50% of the total cooling load of the building by solar absorption cooling system. 120 kW absorption chiller was taken with hot storage tank in solar loop and cold storage tank in load loop. The hot storage tank volume was set to 0.01m^3/m^2 of solar collector area to test the performance at various cold storage tank volumes. They found that when the cold storage tank volume varies between 4 m^3 and 22 m^3, the solar fraction only changes about 2 %. The solar fraction varies between 51% and 57 % when the hot storage tank increases from 2m^3 to 22 m^2. They found that performance of the solar cooling system is most sensitive to the solar collector area followed by the chiller capacity, hot storage tank volume and cold storage tank.

Tsoutsos et al. 2010 accepted that the air conditioning is responsible for a large percentage of the greenhouse and ozone depletion effects. They suggested the solar cooling system for zero emission technologies and to reduce energy consumption and CO_2 emission. In this paper a study is carried out to simulate the solar absorption cooling system for a Greek hospital that required 123911 kWh annual cooling energy. The peak power of cooling was 121 kW and to meet this 70 kW absorption and 50 kW compression chillers were used. They found that 200 m^2 solar thermal collector area is not suitable for this application and solar fraction of 74.23% is achieved with the 500m^2 collector area.

Hang et al. 2011 carried out economical and environmental assessment of an optimized solar cooling system for a medium sized benchmark office building in Los Angeles (California) having the floor area 4983 m^2. The solar cooling system consist evacuated tube collector, hot storage tank, single effect absorption chiller and a auxiliary heater. In this building 150 kW capacity absorption chiller was used with varying collector area of 80-490 m^2. They found that a collector area of 280 m^2 and a storage tank volume 11 $m^3$was optimal configuration corresponding to a solar fraction 83%. The calculated payback was 13.8 years when the 40% subsidy provided on capital investment.

Bajpai 2012 designed and studied an environment friendly vapour absorption refrigeration system of one ton capacity using ammonia and water as working fluid. They suggested that solar heating panel installed on a hostel roof used in the winter for heating that remains idle in the month of summer, can be used for the refrigeration in that time. They found that $24m^2$ solar collector area is required for one ton of refrigeration.

Caciula et al. 2013 carried out a simulation study based on first and second law of thermodynamics using compound parabolic collectors. They developed a mathematical model foe aqua-ammonia based on mass and energy conservation equations. They found that a maximum COP of 0.66 achieved when the generator temperature was 85°C and evaporative temperature is 6°C. The condenser temperature was kept 30°C.

Experimental studies

Duffie et al. in 1963 proposed a combination of LiBr-H_2O in place of the ammonia-water combination. The overall COP of the system varied between 0.11 and 0.15 for average evaporator temperature 9 to 13° C. A cooling rate of one tone for every 18 m^2 of collector area was obtained. The system was commercial available as Arkla unit LiBr-H_2O absorption air conditioner [Kaushik 1989].

A system having the cooling capacity of 10 kW based on NH_3 – H_2O absorption was developed by the Farber et al. in 1966. This system require 37 m^2 of collector area and sufficient to supply energy for space conditioning of a single story house with roof area of 95 m^2. In the steady state the refrigeration system COP was 0.57 operating between weak solution concentration of 0.39 and strong solution concentration of 0.58 [Kaushik 1989].

Sheridan 1972 reported the performance of a Brisbane Solar house using LiBr-H_2O absorption air conditioner. Under transient condition, the COP varied from 0.5 to 0.7 and the room (to be cooled) reached a temperature of 23° C. In this system the condenser and absorber were water cooled. The system also utilized hot water storage and cold water storage facilities. In the hot water storage tank an electrical heater was also used to amplified the solar collection output [Kaushik 1989].

Osman 1985 used the tracking cylindrical parabolic collectors for solar cooling in arid zones in place of flat plate collectors. In this a small micro-motor to track the sun in its daily east-west cycle was used. The motor has a power of 100W with an energy consumption of less than 0.05 kWh per day of full sunshine. The system was installed for cooling a single story house of 264 m^2 consisting of two bedrooms, a dining room, a living room, salon, kitchen and two bathrooms. An 80 m^2 of line concentrator collector area and 8 m^3 storage tank with an insulation of 10 cm Polyurethane were used in the system. They found that if the water is too hot and a fixed flow rate is used there would be wastage of heat and if the water is too cold then the pump will not operate properly. The cooling capacity decreases with an increase in condenser water temperature and it increases with the increase in the generator temperature. The overhall system efficiency was less than 20%.

Hammad et al. 1992 described the performance of non-storage, continuous, solar operated absorption refrigeration unit. They used locally manufactured solar collectors and refrigeration experimental units. The collectors are comprised of a flat plate collector of 3.6 m^2 in series with a parabolic concentrator of 0.15m^2 aperture area. The maxi- mum ideal coefficient of performance of the system was determined to be equal to 1.6, while the peak actual coefficient of performance was determined to be equal to 0.55.The results presented in this paper are based on operation of the unit when there was enough solar energy to power its generator. They found that the performance of the unit depends on generator temperature, evaporator temperature and available solar intensity.

Bansal et al., (1997), designed and fabricated a solar cooling unit on solid-vapour intermittent absorption system, which utilizes thermal energy supplied by the heat pipe vacuum tube solar collectors through thermosyphonic flow of water. In this unit ammonia is used as refrigerant and a mixture of 80% $SrCl_2$ and 20% Graphite is used as sorbent. The cooling capacity of unit is 1.5 kWh/day and the overall COP was found to be 0.81. The theoretical maximum COP is calculated as 0.143 and varies with the climate conditions.

Erhard et al. 1998 simulated and tested a solar-powered absorption cooling machine. The system has the absorber and desorber unit which was mounted inside a concentrating solar collector. In this system the working pair used is NH_3 as refrigerant and $SrCl_2$ as absorbent. Results obtained from field tests were compared with the results obtained from a simulation program developed for this purpose. The overall COP of the cooling system has been calculated as 0.04%.

Hammad et al. 1998 further described the performance of a 1.5-ton solar cooling unit. The unit comprises a 14 m^2 flat-plate solar collector system and five shell and tube heat exchangers. Two major improvements were carried out in this cooling unit with the previous [Hammad et al. 1992]. First they increased the capacity from 0.5 to 1.5 Ton and resulting in increase in the benefit- cost ratio to about 1.4, second use of better technologies manufactured equipments and this enhances the COP from 0.6 to 0.75. The results presented by them was based on the operation of the unit during the sufficient solar radiation hours in April and May, the beginning of the air conditioning season in Jordon. The maximum actual and theoretical COP was observed were 0.85 and 2.7 respectively.

Best et al. (1999) presented a review of solar cooling and refrigeration technologies. The concept of cooling is appealing because the cooling load is roughly in phase with solar energy availability. They conclude that lowering first cost of the system is still main target in order to allow this technology to enter the market. This technology should have economical, technical, social and environmental aspects.

Li et al. 2001 presented the performance of a solar powered air conditioning system with partitioned hot water storage tank. The solar powered air conditioning system consists of a flat- plate collector array of 38m^2 surface area to drive a 4.7 kW chiller cooling capacity . The system operating in partitioned mode have a total solar cooling COP of the system about 0.07 which is about 15% higher than the traditional whole tank mode. The system also starts giving cooling effect nearly 2h earlier and also in cloudy days system was energized in compare to the conventional one.

Asdrubali et al.2005 presented the experimental performances of a LiBr-H_2O absorption refrigerator. The refrigerator was operated by hot water supplied by electrical boiler. Main parameter like temperature, pressure, and flow rates were recorded. Further they also develop a calculation model to simulate a single stage refrigeration machine with H_2O-LiBr and validated by experiments. The result shows that the machine has the highest COP at temperature around 70 °C and feasible to operate this machine with solar collectors.

Izquierdo et al. 2008 determined the performance of a 4.5 kW air cooled, single effect LiBr/H_2O absorption chiller for residential application. The experiment was carried in August 2005 for 20 days period. The hot water inlet temperature in the generator is varied throughout the day from 80°C-107°C. The results shows that for the period as a whole cooling power tended to decline with rising the outdoor dry bulb temperatures. The total energy supplied to the generator came to 1085.5 kWh and the heat removed in the evaporator was 534.5 kWh. The average COP for the 20 days period was 0.49 came down to 0.37 when the electric power used by auxiliary equipment was included.

Pongtornkulpanich et al. 2008 shared the experience with fully operational solar driven 10 ton LiBr/H_2O single effect absorption cooling system. The system was installed for supplying cooling for the main testing building in Naresuan University Thailand. They analyzed the data collected during 2006 and show that 72 m^2 evacuated tube solar collector delivered a yearly average solar fraction of 81%, while LPG –fired backup unit supplied the 19% thermal energy. They show that the initial cost of installation is higher than that of the conventional vapour compression system due to higher cost of solar collector array and chiller. They concluded that technology advancement, large production, and increase in price of electricity in future provide the cost competitive with the conventional system.

Marc et al. 2010 presented an experimental study of a solar cooling absorption system. The system was installed at Reunion Island, located in the southern hemisphere near the Capricorn Tropic. The system was used to achieve effective cooling of classrooms, by a solar cooling system without any backup systems (hot and cold storage). They found that the overhaul electrical and thermal performances are not high. Moreover the objective of the installation of cooling of 4 classrooms without backup system during the occupancy period has been reached. Since the difference between internal and external temperature difference is 6°C. They suggested that if the chiller is undersized and runs in nominal conditions with good performances, thermal comfort inside the building will not be achieved in some critical periods of the year. In this case, thermal comfort can be achieved by ceiling fans.

Praene et al. 2011 presented the simulation and experimental investigation of a solar driven 30 kW LiBr/H_2O single effect absorption cooling system. The system was installed at University of Technology Saint Pierre and used for cooling of four class room. The system comprised a 90m^2 double glazed flat plate collectors, 80 kW cooling tower, 1500 liter capacity hot water storage tank and 1000 liter capacity cold storage tank along with 13 fan coil unit. The first field test result shows that 20 kW is enough to reach the thermal comfort conditions, as there are hot and cold water storage tanks.

Venegas et al. 2011 presented an experimental performance of a solar cooling facility along one summer season using a commercial single effect water lithium bromide absorption chiller aiming at domestic application. They performed statistical analysis with the gathering data influence on five daily operational variables on the performance. These are solar energy received along a day, average ambient temperature, wind velocity magnitude, wind direction and the relative humidity. They found that daily average COP and Cooling Energy are mainly influenced by solar energy received in a day, wind velocity magnitude and direction. The time along which cold water is produced is highly sensitive to solar energy received in a day and ambient temperature.

Yin et al. 2013 presented the experimental investigation of mini type solar – powered absorption cooling system.The solar cooling system comprised with a 96

m^2 solar collector’s area and 3 m^3 hot water storage tank, 8kW cooling machine and cooling tower. The system used for air conditioning of a 50m^2 test room. The experimental result showed that the solar cooling system could meet the indoor thermal comfort demand with the comfort level of A and power consumption was reduced 43.5%.

Hang et al. 2014 presented the experimental based energy analysis of solar cooling system at university of Californian. A 23kW double effect absorption chiller was powered by a field of 54 m^2 compound parabolic concentrator. Experimental result showed that the daily average collector efficiency is in the range of 36 % to 39%. The average COP of the chiller is between 0.91-1.02. Daily solar COP 0.374 was achieved. Table 2.1 shows the summary of solar absorption cooling systems.

Megallanes et al. 2014 presented the experimental result of the vapour absorption cooling system. The system was designed using ammonia –lithium nitrate solution. The capacity of system was 3kW. The result showed that the system was produced 2.7kW cooling capacity at 95°C hot water temperature and evaporator temperature was reached 1°C. They conclude that the system works with good efficiency and do not require rectifier.

Table 2.1 Summary of solar absorption cooling systems

Reference	Year	Working pair	Place	Application	Capacity	Solar collector type and area (m^2)	Generator Temperature	Solar Fraction	COP	Type
Duffie et al.	1963	LiBr-Water		Chiller		$18m^2/kW_c$			0.15	Experimental
Osman	1985	LiBr	Kuwait	Absorption air conditioner	3TR	Concentrator - 80 m^2	98.9°C		0.20	Experimental
Hammad et al.	1992	LiBr	Jordan	Refrigerator		3.6 m^2	65°C		0.57	Experimental
Namir F.Saman	1996	LiBr-Water	Iraq	Chiller	2TR		80-95 °C		0.80	Simulation
Bell et al.	1996	LiBr-Water	Saudi Arabia	Chiller			68°C		0.6-0.8	Simulation
Ghaddar et al.	1997	LiBr-Water	Lebanon	Chiller	10.5kW	23.3 m^2/Ton	65-85°C	20-44%		Simulation
Erhard et al.	1997	NH_3-$SrCl_2$	Germany	Refrigerator	15-18W	0.844 m^2	103°C		COP_s0.04	Experimental
Bansal et al.	1997	NH_3+80% $SrCl_2$ and 20% Graphite	India	Refrigerator		ETC-2.1m^2	80°C		COP_s0.081	Experimental
Hammad et al.	1998	LiBr-Water	Jordan	Refrigerator	3.5 kW	14 m^2	85°C		0.75	Experimental
Li et al.	2001	LiBr-Water	Hong Kong	Chiller	4.7 kW	38 m^2	88°C		COP_s0.07	Experimental
Florides et al.	2002	LiBr-Water	Cyprus	Chiller	11 kW	CPC-15m^2	87°C		0.74	Simulation
Balghouthi et al.	2005	LiBr-Water	Tunisia	Chiller	10kW	FPC-30 m^2	120°C			Simulation
Assilzdeh et al.	2005	LiBr-Water	Malaysia	Chiller	3.5kW	ETC-35m^2	65-70°C		0.32	Simulation
Asdrubali et al.	2005	LiBr-Water	Italy	Chiller			70°C			Experimental
Mazloumi et al.	2008	LiBr-Water	Iran	Chiller	17.5 kW	57.6 m^2				Simulation
Izquierdo et al.	2008	LiBr-Water	Spain	Chiller	4.5 kW		107°C		0.37	Experimental

Reference	Year	Working pair	Place	Application	Capacity	Solar collector type and area (m^2)	Generator Temperature	Solar Fraction	COP	Type
Ali et al.	2008	LiBr-Water	Germany	Chiller	35.17kW	ETC-108m^2	87 °C	33-41%	0.41	Experimental
Pongtornk et al.	2008	LiBr-Water	Thailand	Chiller	35kW	ETC-72 m^2	75°C	81%	0.70	Experimental
Mateus et al.	2009	LiBr-Water	Portugal	Chiller	10kW	FPC	72°C	20-60%		Simulation
Eicker et al.	2009	LiBr-Water	Germany	Chiller		2 - 4 m^2/kW cooling power		80%		Simulation
Alili et al.	2010	NH_3 –water	Abu Dhabi	Chiller	10 kW_c	6m^2/kW_c	85°C		0.54	Simulation
Hang et al.	2010	LiBr-Water		Chiller	120 kW	ETC-200m^2		51-57%		Simulation
Tsoutsos et al.	2010	LiBr-Water	Greece	Chiller	70 kW	500 m^2		74.23%	0.70	Simulation
Marc et al.	2010	LiBr-Water	France	Chiller	30 kW	FPC- 90 m^2	90°C		0.30	Experimental
Hang et al.	2011	LiBr-Water	California	Chiller	150 kW	80-490 m^2	98°C	83%	0.30	Simulation
Praene et al	2011	LiBr-Water	France	Chiller	35 kW	FPC- 90 m^2	95°C			Experimental
Bajpai 2012	2012	NH_3 –water	India	Refrigerator	3.5 kW	24 m^2	84 °C		0.69	Simulation
Caciula et al.	2013	NH_3 –water	Brasov	Chiller		CPC-2.42m2	85 °C		0.66	Simulation
Yin et al.	2013	LiBr-Water	China	Chiller	8 kW	96 m^2	90°C		0.31	Experimental
Hang et al.	2014	LiBr-Water	United states	Chiller	23 kW	54 m^2	155-180°C	55-68%	0.91	Experimental
Megallanes et al.	2014	NH_3-Lithium Nitrate	Mexico	Refrigerator	3kW	-	95°C		0.70	Experimental

2.1.2 Solar vapour adsorption system studies

The adsorption phenomenon is the result from the interaction between a solid and a fluid (refrigerant) based on a physical or chemical reaction. Physical adsorption occurs when the molecules of refrigerant (adsorbate) fix themselves at the surface of a porous solid element (adsorbent) due to Vander Walls forces. By applying heat, the adsorbate molecules can be released (desorption), whereby this is a reversible process. In the chemical adsorption the ionic or covalent bonds formed between the adsorbate molecules and the solid substance. The bonding forces are much greater than that of physical adsorption releasing more heat. However the process cannot be easily reversed [Fernades et al. 2014]. The adsorption refrigeration system studies are divided into two group i.e. modeling and simulation studies and experimental studies.

Modeling and simulation studies

Lloeje et al. 1995 presented the mathematical model of solar powered adsorption refrigerator. The refrigerator used $CaCl_2$ as adsorbent and NH_3 as refrigerant. The granular adsorbent was packed in the tubes of a double glazed flat plate solar collector. The condenser tubes are cooled by water whose temperature is maintained below atmospheric temperature. They found that a peak COP of 0.14 was observed when the outer tube internal diameter was 50mm.

Boubakri et al. 2000 presented a numerical model of a solar cooling unit having a flat plate solar collector/condenser with a surface area of 1 m^2, consisting of two identical shells, the upper one operating as a solar collector and lowers one as a condenser. Considering the systems components optimal values and metrological condition of France, the estimated daily ice production was about 11.5 kg/m^2 with a solar COP of 0.19 for a daily solar radiation of 29 MJ/m^2.

Leite et al. 2000 presented a numerical model for an adsorption solar cooling system using the activated carbon methanol pair. The solar powered ice maker is constituted of the following parts; a reactor containing an adsorptive bed coupled to a static solar collector covered by transparent insulation material (TIM), a condenser and an evaporator. The machine performance was evaluated using the metrological data of Joao Pessoa Brazil whose climate is typically hot and humid. The TIM covers proved 40 % more efficient than the single cover system. The average COP was 0.13 and ice production of 7-10 kg/day per square meter of solar collection surface respectively for march and December with the solar irradiation from 20-23MJ/m^2.

Li et al. 2003 presented the simulation results of a solar powered adsorption refrigerator, in which the zeolite – water pair is used. The evacuated tube are used to collect the solar energy .In order to reduce the heat losses, selective materials has been coated on the surface of the inner glass tubes. They found that the adsorbent temperature was reached around 200°C and the overall system performance is relatively high compared to the previous solar absorption refrigerators , reaching theoretical COP values higher than 0.25.

Aghbalou et al. 2004 developed a numerical model to study an adsorption refrigeration system containing a parabolic solar collector, which transfers heat to the adsorbent bed through heat pipes, also promoting the heat dissipation in the adsorption stage. They calculated temperature and adsorbed mass transfer into the generator at each step time for a given heat flux. They found that at ambient temperature 24.2°C the COP of system was reached 0.144 when the evaporator temperature was 0°C, condenser temperature 30°C and generator temperature was 100°C.

Boubarki et al. 2006 presented the performance of an adsorptive solar ice maker (ASIM) operating with a single double function heat exchanger (condenser/evaporator). They showed that with a consistent design of the different components of this machine the daily ice production could exceed 5.2 kg with a COP of more than 0.14. This value of COP was very interesting in comparison with those usually obtained from the ASIMs operating with separate condenser and evaporator, i.e. 0.08-0.2.

Mers et al. 2006 presented numerical model describing the heat and mass transfer processes in a cylindrical finned reactor of a solar adsorption refrigerator.

The optimization results showed that introduction of 6 fins, compared with a bed without fins, increases the solar COP of the system from 0.07 to 0.11.

Vasta et al. 2008 presented the numerical model of a solar adsorption refrigerator. They carried out dynamic simulation for the different stages of the thermodynamic cycle of refrigerator component. The system comprised a 1.5 m^2 solar collector containing a adsorbent bed, a condenser and a cold box. They found that most of the year, system has the ability to produce between 4 and 5 kg ice per day. In the colder months system produce only 2-3.5 kg of ice per day. The average monthly net solar COP ranged from 0.045 to 0.11 with a yearly average COP of 0.07.

Gonzalez et al. 2009 presented the simulation of a solar powered solid adsorption chiller with a CPC collector using methanol activated carbon pair. The model is based on assigning constant thermal exchange parameters to the main elements of the systems like generator, condenser, evaporator and cold box. It was possible to obtain solar COP values between 0.90 and 0.12, corresponding to daily ice productions of 0.4 kg/m^2 and 0.06 kg/m^2 respectively.

Fadar et al. 2009 simulated a solar adsorption refrigerator in summer climate in morocco. The system comprised a parabolic solar collector connected to a cylindrical absorber through a water heat pipe. The model was developed in FORTRAN, based on thermodynamics of the adsorption process, heat and mass transfer and energy balance within the porous medium. The influence of several parameters were analyzed and it was found that the COP increases as the adsorbent mass is increased up to a critical value of 14.5 kg which corresponding to 72.8 cm collector opening and a solar COP of 0.18.

Maggio et al. 2009 used a novel composite sorbent lithium chloride in silica gel pores for the solar powered ice makers. They developed a mathematical model which was used in order to calculate the performance of an ice maker using this material as adsorbent and methanol as adsorbate. The system consists of a 1.5 m^2 flat plate solar collector, a condenser and an evaporator inside a cold box. The maximum observed COP was 0.33 with a maximum daily production of 20 kg ice per m^2 of collector.

Hassan et al. 2011 presented a simulation model of a tubular solar adsorption refrigeration system using carbon-methanol working pair. The model have the 1 m^2 flat plate solar collector consists of several steel pipes containing the adsorbent. The model accounted the variation of ambient temperature and solar radiation along the day. It was found that the COP value was 0.21 while the solar radiation intensity reached a maximum of 900 W/m^2.

Qasem et al. 2013 addressed the factors that can improve the performance of an activated carbon/methanol intermittent solar adsorption ice marker. It optimizes the ice maker under Dhahran climate with the MATLAB program to improve the performance and to increase the ice production per day per square meter of the solar collector. The system can produce from 5 kg up to 13 kg of ice per day per m^2 of collector area with improved solar coefficients of performance (SCOP) of 0.12 and 0.24 in the hot and the cold days respectively. They suggested that the optimized solar refrigerator will be beneficial to producing ice in grid-off rural zones.

Experimental studies

Pons et al. 1986 developed a solar ice maker prototype comprising of four flat type solar collector having 6 m^2 area equipped with dampers to increase the night cooling of the adsorbent bed, two air cooled condensers and an evaporator able to produce 30-35 kg of ice per day achieving a net solar COP of 0.10 -0.12, for clear sky conditions.

Critoph 1994 developed a simple low cost solar refrigerator for vaccine storage for the poor regions. They used transparent insulation material (TIM) to reduce collector heat losses. The system was operated at high pressure with the activated carbon ammonia pair. Flat plate solar collector area of 1.4 m^2 was used which contained the adsorbent material inside. The experiment result showed that the evaporator temperature reached – 1°C, producing 3-4 kg ice per day with a net solar COP of 0.04. Further in 1997 the same research team presented the experimental results of a solar adsorption refrigerator and reported higher COP in the range of 0.061 to 0.071 using three types of collector: single glazed, double glazed and single glazed with transparent thermal insulation [Critoph et al. 1997].

Mhiri et al. 1996 described the study of a solar adsorption refrigerator working with the activated carbon- methanol pair in order to build an industrial system. The maximum solar COP ranged from 0.14-0.20, for a solar radiation flux between 5 and 17 MJ/m^2 respectively. The system produced daily ice production of 12.2 kg at -5°C with a collecting area of 4 m^2.

Sumathy et al. 1999 designed and built a solar refrigerator in Hong Kong. A 0.92 m^2 flat plate solar collector and activated carbon –methanol pair was used. They found that activated carbon and methanol is suitable for refrigeration compare to $CaCl_2/NH_3$, H_2O/NH_3, and NH_3/Sodium Thiocyanate etc. The system was capable of producing 4-5 kg of ice daily at a temperature of -6 °C in the evaporator , for a daily solar radiation between 17 and 19 MJ/m^2, and achieving solar COP values of 0.1- 0.12.

Li et al. 2002 built a solid adsorption refrigeration ice maker for demonstration purpose working with the activated carbon and methanol as the working pair. The adsorbent bed is constructed of two flat-plate collectors, with a total surface area of 1.5 m^2. In order to improve heat transfer between the front side and the adsorbent, many fins (Aluminum) was placed inside the collector. The experimental results show that this machine can produce 4–5 kg of ice after receiving 14–16 MJ of radiation energy with a surface area of 0.75 m^2 , while producing 7– 10 kg of ice after receiving 28–30 MJ of radiation energy with 1.5 m^2.

Buchter et al. 2003 tested a solar refrigerator with a 2 m^2 solar collector, equipped with ventilation dampers to increase night cooling of the adsorbent bed. The solar COP of this machine ranged between 0.09-0.13 when the daily solar radiation values were between 22 and 25 MJ/m^2. The ice produced during the day was used to preserve the temperature of the cold box at 5°C.

Li et al. 2004 described the development of a solar refrigerator operating without any valves or moving parts, manufactured and tested in China. The 0.94 m^2 flat plate collector area consisted of an insulated box whose surface was coated with a selective coating and with the adsorber placed inside, where several fins increased the heat transfer. The system produced 4 kg of ice per day and per m^2 of collecting area achieving a solar COP between 0.11 and 0.12.

Boubakri et al. 2006 designed a new prototype containing only one double function heat exchanger (condenser/evaporator) which works alternatively as a condenser and as an evaporator. In this ventilation was provided to increase the night cooling effect of the adsorbent bed. They found that this configuration considerably reduced the weight of the whole system and therefore the manufacturing costs.

Leite et al. 2007 analyzed the performance parameters of an experimental solar adsorptive ice maker. The system used a 2 m^2 collector area. The solar collector/adsorber is multi tubular with an opaque black radiation absorbing surfaces and thermally insulated by a TIM. Experimental test conducted in a region in Brazil close to the equator in clear, partly cloudy and overcast sky conditions, resulting in evaporator temperature of -4.6 C, -2.5 C and -1.8 C and daily ice production of 6.05, 2.10 and 0 kg per m^2 of collector respectively.

Ahmad et al. 2011 described the construction of a solar adsorption refrigerator operating with the activated carbon methanol. To increase the heat transfer processes small copper particles were added to the adsorber bed. A reflector was used to concentrate the solar radiation. The system was tested in the metrological conditions of Cairo resulting in the daily ice production of 1.38 – 3.25 kg per m^2 of collector area with a solar COP ranging between 0.07 and 0.11.

Omisanya et al. 2012 presented the design and production of a solar powered Zeolite-water adsorption refrigerator using concentrating parabolic collector (CPC). An array of two CPCs with a total collector area of 1.029 m^2, concentration ratio of 1.8 was used. The experimental test resulted in an average temperature of 11°C in the evaporator throughout the day time period and a maximum temperature of 110 C in the absorber. The measured hourly instantaneous COP ranges from 0.2 to 2.5 with the hourly insolation ranges from 34 W/m^2 to 345 W/m^2.

Santori et al. 2014 developed a new versatile, solar driven ice maker operating with the activated carbon/ methanol adsorption pair. The field tests carried out on February and March 2013, showed that the prototype is able to produce up to 5 kg ice with a solar COP of about 0.08. The solar radiation is collected by a 1.2 m^2 collector area. Table 2.2 shows the summary of solar adsorption cooling systems. Table 2.2 shows the summary of adsorption cooling systems.

Table 2.2 Summary of solar adsorption cooling systems

Reference	Year	Working pair	Country	Application	Solar collector type	Area (m^2)	Ice Produced	Solar COP	Evaporator Temperature (°C)	Type
Pons et al.	1986	Activated carbon Methanol	France	Ice maker	Flat plate	6	6 kg/m^2 day	0.10-0.12	-5 °C	Experimental
Critoph et al.	1994	Activated carbon Ammonia	England	Ice maker	Flat plate	1.4		0.04	-1 °C	Experimental
lloeje et al.	1995	$CaCl_2$- Ammonia	Nigeria	Ice maker	Flat plate			0.14		Simulation
Mhiri et al.	1996	Activated carbon Methanol	Tunisia	Ice maker	Flat plate	4	12.2 kg/day	0.14-0.19	-5°C	Experimental
Critoph et al.	1997	Activated carbon Ammonia	England	Ice maker	Flate plate	1.4		0.061-0.071	0°C	Experimental
Sumathy et al.	1999	Activated carbon Methanol	China	Ice maker	Flat plate	0.92	4-5 kg/day	0.10-0.12	-6 °C	Experimental
Boubakri et al.	2000	Activated carbon Methanol	France	Icemaker	Flat Plate	1	11.5 kg/day	0.19		Simulation
Leite et al.	2000	Activated carbon Methanol	Brazil	Ice maker	Flat plate	1	7-10kg/day	0.124-0.155	-2 °C	Simulation
Li et al.	2000	Activated carbon Methanol	China	Ice maker	Flat plate	1.5	7-10 kg/day	0.13-0.14		Experimental
Buchter et al.	2003	Activated carbon Methanol	Burkino Faso	Ice maker	Flat plate	2		0.09-0.13		Experimental
Li et al.	2004	Activated carbon Methanol	China	Ice maker	Flat plate	0.94	4 kg/m^2 day	0.11-0.12		Experimental
Aghbalou et al.	2004	Activated carbon Ammonia	Spain		CPC			0.144		Simulation

Reference	Year	Working pair	Country	Application	Solar collector type	Area (m^2)	Ice Produced	Solar COP	Evaporator Temperature (°C)	Type
Boubakri et al.	2006	Activated carbon Methanol	France	Ice maker	Flat Plate	1	5.2 kg/day	0.14	-10°C	Simulation
Mers et al.	2006	Activated carbon Ammonia	Morocco	Refrigerator	Flat plate			0.105		Simulation
Leite et al.	2007	Activated carbon Methanol	Brazil	Ice maker	Flat plate + Reflector	2	6.05kg/m^2	0.085	-4.6 °C	Experimental
Vasta et al.	2008	Activated carbon Methanol	Italy	Ice maker	Flat plate	1.5	2-5 kg/day	0.045-0.11		Simulation
Gonzalez et al.	2009	Activated carbon Methanol	Spain	Ice maker	CPC	0.55	0.06-0.4kg/m^2	0.11-0.87		Simulation
Fader et al.	2009	Activated carbon Ammonia	Morocco	Refrigerator	CPC+ heat pipe			0.18		Simulation
Maggio et al.	2009	Silica-gel+LiCl-Methanol	Italy	Ice maker	Flat plate	1.5	20kg/m^2	0.33		Simulation
Hasan et al.	2011	Activated carbon Methanol	Canada		Flat plate	1		0.211		Simulation
Ahmed et al.	2011	Activated carbon Methanol	Egypt	Ice maker	Flat plate+ Reflector		1.38-3.25kg/m^2	0.07-0.11		Experimental
Omisanya et al.	2012	Zeolite water	Nigeria	Water cooler	CPC	1		0.8-1.5	11°C	Experimental
Qasem et al.	2013	Activated carbon Methanol	Saudi Arabia	Ice maker	Flat plate	1	13 kg/day	0.24	-4°C	Simulation
Santori et al.	2014	Activated carbon Methanol	Italy	Ice maker	Flat plate	1.2	5 kg/day	0.08	-12.4° C	Experimental

2.1.3 Solar desiccant cooling system studies

In the desiccant cooling the incoming air stream is dehumidified by forcing it through a desiccant material after it the air is dried to the desired indoor temperature. For the continuous working of the system, water vapour adsorbed/absorbed are to be driven out of the desiccant material (regeneration) so it can be dried to adsorb water vapour in the next cycle. The system uses natural substance as working fluid and can be powered by solar energy. A desiccant cooling system is made of three components, namely the regeneration heat source, the dehumidifier (desiccant material), and the cooling unit. The desiccants are natural or synthetic substances which has the ability to absorb or adsorb water vapour due to the difference of water vapour pressure between the surrounding air and the desiccant surface. They are encountered in both liquid and solid states [Daou et al. 2006, Ge et al. 2014].

Solid desiccant dehumidifier is a slow rotating desiccant wheel or a periodically regenerated adsorbent bed. When the liquid desiccant is used, the dehumidifier (absorber) is equipment where the liquid desiccant is contacted with the processed air stream. The cooling unit may be the evaporator of a conventional air conditioner or an evaporative cooler. The role of the cooling unit is to handle the sensible load while the latent load is removed by the desiccant. The regeneration heat source supplies the thermal energy to root out the moisture that the desiccant had gathered during the sorption phase. A variety of possible energy sources may be utilized because a thermal energy source is required. It includes solar energy, waste heat, and natural gas heating, and the possibility of energy recovery within the system.

Based on which auxiliary refrigeration system is adopted, the systems are divided into two categories: separate solar powered desiccant cooling system and hybrid solar powered desiccant cooling systems. The desiccant cooling systems studies divided into two group i.e. modeling and simulation studies and experimental studies.

Modeling and simulation studies

Techajunta et al.1999 presented the analytical study to evaluate the performance of a desiccant cooling system. They used silica gel as desiccant.

Incandescent electric bulbs were used to simulate solar irradiation. The regeneration rate was found to be strongly dependent on the solar radiation intensity while its dependence on the air-flow rate was found to be weak.

Khalid 2001 evaluated the performance of a solar assisted heating and desiccant cooling system through computer simulation. The system was used for heating & cooling of a two story residence located in Bagdad. The solar heating system comprised a solar air heater array, rock bed storage and auxiliary heat source. For the cooling system a rotary desiccant dehumidifier, sensible cooler and evaporative cooler was used. In winter heat collected from solar collector was supplied to conditioned room for heating purpose, and a rock bed storage unit and auxiliary heat source were adopted. In summer a ventilation mode was used to provide cooling power. It was found that regeneration temperature of 62 °C could be reached by solar collector alone.

White et al. 2009 developed a simulation model in TRNSYS to study performance of the system in three cities in Australia: the warm and temperate climates of Melbourne and Sydney and the tropical climate of Darwin. The system comprised of a desiccant wheel, heat recovery exchanger along with indirect evaporative cooler and direct evaporative cooler. The result showed that increasing collector area, air flow rate and effectiveness of indirect cooler reduced the frequency of high temperate events in the occupied space. In the warm temperate climate high ventilation rates enabled comfort conditions to be maintained at or near acceptable levels in the occupied spaces.

Enteria 2012 presented the numerical investigation of the developed solar-desiccant cooling system. Two different desiccant wheel coating materials – the Silica-Gel (SiO_2) and the Titanium Dioxide (TiO_2) was used in the system. The system was applied in temperate climate (Beijing and Tokyo), subtropical climate (Taipei and Hong Kong) and tropical climate (Manila and Singapore). The study showed that the specification of the solar-desiccant cooling system varies depending on the climatic conditions. It showed that the required flat plate collector area was getting larger from the temperate climate to the tropical climate. The storage tank requirement was getting bigger in the tropical climate compared to the subtropical and temperate climate. With regard to the new material, Titanium Dioxide, has been proven to be a good alternative material since it can provide lower indoor temperature and humidity ratio with higher cooling performance than the silica-gel.

Guidara et al. 2013 developed a new solid desiccant air conditioner unit. They simulated the system in different mode of operation in three climates. Performance of the system was simulated in three representative cities with different climatic condition in Tunisia. It was found that the conditioned space with respect to each mode of functioning has comfortable environment for occupants.

Experimental studies

Alizadeh et al. 2002 designed a liquid desiccant cooling system. They used fored parallel flow type solar collector as regenerator. The aqueous solution of calcium chloride as desiccant was used. They studied the influence of parameters, such as air and desiccant solution flow rates and the weather conditions on the regenerator's performance. They found that the efficiency of solar collector generally increased with the increase of the air mass flow-rate. An optimum value of the air flow-rate at which the efficiency was maximum also predicted. A strong influence of the solar insolation on the collector's thermal performance was also observed.

Bourdoukan et al. 2008 adopted the heat pipe vacuum collectors in place of flat plate collector to operate a desiccant cooling system. They developed a mathematical model of collector and storage tank (Stratified). Further an experimental setup was built in 2009. The result shows that high regeneration temperature was achieved in compare to the flat plate. The experimental result showed that theoretical COP was 0.45. The system was able to indoor maintain environment at comfort condition at 26.5 °C and Electrical COP of 4.3 was obtained.

Enteria et al. 2010 developed a novel solar cooling and heating system. It consisted of two subsystems, the thermal energy subsystem and the desiccant cooling subsystem. It utilized the cheap electric energy at night and the free daytime solar energy. The system is to produce cooling during summer and hot water during winter. The result shows that the thermal energy subsystem functioned according to its expected performance in the collection of solar energy and thermal storage. The desiccant cooling subsystem mitigated temperature and humidity content of the air using solar energy and a minimal electrical back-up.

Preisler et al. 2012 investigated annual performance of an actual desiccant evaporative cooling system. The experimental demonstration was built in an office building in Vienna, Austria. The system comprised of 285 m^2 flat plate collector along with 15000 liter solar thermal storage. The evaluation of the Austrian DEC systems in the ENERGY base office building made clear that solar driven DEC systems have high primary energy saving potentials compared to a reference system with a air handling unit using compression chillers for air-conditioning. The solar driven DEC system achieved 60.5% primary energy savings compared to a reference system. The evaluation of the operation modes showed that the sorption rotor was used most of the time for heating and humidity recovery (87.5% of the operating hours) and only for less operating hours as desiccant rotor for dehumidification purposes (12.0% of the operating hours). Table 2.3 shows the summary of solar desiccant cooling systems.

Table 2.3 Summary of solar desiccant cooling systems

Reference	Year	Desiccant Material	Desiccant cooling subsystem	Solar collector type	Area (m^2)	Overall system performance	Type
Techajunta et al.	1999	Silica gel		Flat plate		Regeneration rate 0.03-0.1 kg/hr Dehumidification rate =0.06 kg/hr Specific humidity ration 0.01	Experimental
Khalid et al.	2001	Silica gel	Desiccant wheel Evaporative cooling system	Flat plate water collector	54 m^2	COP_{total}= 1.5-5.5 Regeneration temperature 62°C Mass flux = 0.06 kg/s m_2	Simulation
Bourdoukan et al.	2008	Silica gel	Desiccant wheel Evaporative cooling system	Heat pipe vaccum tube collector	205-300 m^2	Overall efficiency 50-64% Solar fraction = 87-97 %	Simulation
Bourdoukan et al.	2008	Silica gel	Desiccant wheel Evaporative cooling system	Heat pipe vaccum tube collector	40 m^2	Temperature indoor 26.5 °C Specific humidity indoor 12-14g/kg of dry air COP_{el} 4.3	Experimental
White et al.	2009		Hybrid	Flat plate water collector	100 m^2	Temperature achieved = 22-30 °C Specific humidity = 10-18 g/kg of dry air	Simulation
Enteria et al.	2010	Silica gel	Desiccant wheel Evaporative cooling system	Flat plate water collector	10 m^2	RH_{amb}= 60% Regeneration Temperature 60-75 °C Temperature achieved = 26.1-27° C Specific humidity 14.3 g/kg of dry air COP total= 0.35-0.44	Experimental

Reference	Year	Desiccant Material	Desiccant cooling subsystem	Solar collector type	Area (m^2)	Overall system performance	Type
Ge et al.	2010	Silica gel + lithium chloride	Desiccant wheel Evaporative cooling system	Vaccum tube water collector	550 m^2	Temperature indoor 20.4-26.2 °C Specific humidity indoor 10.7-11.3g/kg of dry air	Simulation
Preisler et al	2012	Lithium chloride	Desiccant wheel Evaporative cooling system	Flat plate water collector	285 m^2	Dehumidification 2.8g/kg for 62.1% and is between 3.0and 4.4 g/kg for 37.9% of the operating hours COP_{el} =7 Primary energy savings 60.5%	Experimental
Enteria et al.	2012	Silica gel	Desiccant wheel Evaporative cooling system	Flat plate water collector	10-12 m^2	Temperature achieved 23.1 Specfifc humidity 7.6 g/kg of dry air COP_{el} = 1.5-1.7	Simulation
Li et al.	2012	Silica gel + lithium chloride	Desiccant wheel Evaporative cooling system	Evacuated tube air collector	120 m^2	Temperature indoor 18-20.1 °C Dehumidification 6-10g/kg.	Experiment
Guidara et al.	2013	Silica gel	Desiccant wheel Evaporative cooling system	Flat plate water collector		Temperature 20.3, 22 and 24.7° C for Bizerte, Ramada, Djerba (Tunisia) respectively Specific humidity 7.4, 7.3 and 9.4 g/kg of dry air	Simulation

2.1.4 Solar hybrid desiccant system studies

Desiccant cooling system has good capacity of handling latent load, and conventional vapour compression system can effectively remove sensible load compared with evaporative cooling process. The combination of desiccant and compression system is known as hybrid desiccant system. Following are the studies related to the hybrid desiccant system [Ge et al. 2014].

Yadav 1995 simulated a hybrid desiccant cooling system consisting a traditional compression air conditioning system with a liquid desiccant dehumidifier regenerated by solar energy. The study showed when the latent load constitutes 90% of the total cooling load; the system can produce up to 80% of energy savings.

Halliday et al. 2002 carried out the feasible study in Europe using real summer time metrological data. Several representative cities in Europe from north to south were selected and hot days occurred in a year 1996 were considered. It was assumed that supply air was maintained at 18.1°C in the simulation process. Performance of the system was evaluated by energy saving ratio compared with conventional gas powered desiccant cooling system. It was found that except for Osla, gas energy savings up to 25.1-46.5% was obtained.

Khalid et al. 2009 built up a solar desiccant hybrid system in Karachi, Pakistan. This system adopted two indirect evaporative coolers instead of direct evaporative coolers in process air side. It was found that desiccant wheel cooling system alone could not supply air to comfort conditions due to high latent and sensible loads, auxiliary VCS was required under such conditions.

La et al. 2011 presented experimental investigation of a solar hybrid air conditioning system. The system was hybrid of a 10kW desiccant and 20kW vapour absorption air conditioning. It comprised a flat plate solar collector of 72 m^2, hot storage tank and cooling tower. The experiment result showed that under typical weather condition the solar driven desiccant unit achieved an average cooling capacity 10.9 kW i.e. 35.7% of cooling capacity provided by hybrid system with corresponding average thermal COP 1.24. The desiccant cooling unit itself removed

57%, 69%, 55% of seasonal moisture load for temperate, humid and extreme humid weather conditions.

Fong et al. 2011 presented a simulation study of a solid hybrid desiccant cooling system (SHDCS) for a restaurant in Hong Kong. They applied hybrid cooling system modeled in TRNSYS. The latent and sensible loads for the Chinese restaurant are 13 kW and 19 kW respectively. The desiccant system was designed to tackle the latent load and vapour compression system to cater the sensible load. Results showed that the hybrid system could maintain indoor temperature as well as humidity ratio. They calculated that annual primary energy savings was 49.5%.

Finocchiaro et al 2012 pointed out that due to limited cooling capacity of desiccant evaporative cooling system, return air temperature is high. In order to overcome this problem a packed wet heat exchanger was proposed to replace sensible heat exchanger to realize much more sensible load removal. Experimental results show that due to the optimization of the indirect evaporative cooling process, a supply temperature in the range of 21-22 °C can be achieved.

Baniyounes et al.2012 investigated the performance of hybrid desiccant cooling system numerically and experimentally. The simulation model was developed on TRNSYS software and the model was adopted to quantify annual technical performance and energy savings. The simulation result showed that the total annual cooling load was 6428 kWh. It reached its peak in the month of December. Hybrid system provided the air at temperature 25-27 °C and relative humidity ratio of 60%. Based on theoretical analysis, experimental setup was constructed having a 10 m^2 collector area. Experimental results were agreed with the simulation and annual solar fraction of 22% is achieved with a COP 0.7.

2.1.5 Working fluid and material studies

Working pairs for absorption systems

In the absorption cooling system a number of refrigerant – absorbent pairs are used. The most common pairs are LiBr-water and Ammonia-water. These two pairs offer good thermodynamic and environmentally benign performance [Florides et al 2003]. These pairs should have the number of important requirement like; it should not form the solid phase over the range of composition and temperature to which it will be subjected. The refrigerant should be more volatile than the absorbent. The absorbent should have a strong affinity with the refrigerant.

The generator temperatures needed for the LiBr- water pair are lower (75-120 °C) and this temperature range can be achieved by the flat plate, evacuated tube and compound parabolic collectors that are lower cost and easier to install. The use of this pair is limited by the evaporator temperature since water is working as refrigerant hence not suitable for below 5 °C. The ammonia –water pair working on high temperature range (125-170 °C). This temperature can be achieved by concentrator and required tracking systems, which increase the cost. In this pair, ammonia works as a refrigerant so a temperature below 0°C can be achieved. Broadly speaking NH_3-H_2O is used for refrigeration and air conditioning both and LiBr- H_2O is for air conditioning purpose [Fan et al. 2007].

Other working pairs are also investigated. Ehard et al. 1997 developed a solar powered cooling machine using new NH_3 $SrCl_2$ as working pair. The overall COP of the cooling system has been attained between 0.045-0.082. Bansal et al 1997 use the mixture of 80% $SrCl_2$ and 20% Graphite as absorbent and ammonia as refrigerant. The theoretical COP is 0.143 and depends on climatic conditions. Medrano et al.2001 discussed the potential of using organic fluid mixtures trifluoroethanol (TFE)- tetratehylenglycol dimethlether (TEGDME) and methanol-TEGDME as working pair. Megallances et al 2014 used Ammonia-lithium nitrate solution to operate vapour absorption system and system was worked with good efficiency.

Working pairs for adsorption systems

There are several possible adsorbent-adsorbate working pairs that can be used in the adsorption cooling systems. The selection of working pair depends on the temperature of heat source, the properties of working pair, affinity between them, availability and environmental impacts [Fernades et al. 2014].

The adsorbate or refrigerant should have low evaporation temperature, small molecular size, high latent heat of vaporization, low specific volume in liquid states, high thermal conductivity, low viscosity, chemical stability, low saturation pressures, non toxic, non corrosive and non inflammable. The natural refrigerants used in the adsorption refrigeration system generally have zero environment impact. The most commonly used refrigerants are ammonia, methanol and water.

The adsorbent must have the ability to adsorb a large amount of refrigerant and desorb it when heated. It should have the low specific heat, good thermal conductivity, non toxic, non corrosive, chemically and physically compatible. The most suitable adsorbent materials must be porous enough to allow for a large refrigerant quantity. The most common used adsorbents are activated carbon, zeolite and silica-gel. Wang et al. 1997 studied a specially treated activated carbon fiber and found that it has two to three times higher capacity for methanol adsorption than standard activated carbon. Also Wang et al. 2014 and Alili et al. 2014 presented several studies regarding the performance enhancement of several adsorbents by combination with other substances.

The most common used working pairs are silica gel - water, zeolite- water, activated carbon methanol and activated carbon ammonia. Silica gel - water is ideal for solar refrigeration systems due to its low regeneration temperature below 85°C and water have the advantage of greater latent heat. However this pair has a low adsorption capacity and requires vacuum conditions in the system [Wang et al. 2010, 2014].

Activated carbon-methanol is another important working pairs used in the adsorption system. It requires low regeneration temperature of around 120°C, and having large cyclic adsorption capacity. However activated carbon has a low thermal conductivity, causing a reduction in the system performance.[Wang et al. 2010 , Mahesh et al .2012]

Activated carbon ammonia pair requires regeneration temperature of greater than 150 °C. Its adsorption capacity is similar to activated carbon methanol pair, but it requires higher operating pressures, which enhances the heat and mass transfer and reduces the cycle time. Using this pair toxicity is the major problem.

For zeolite- water pair, the regeneration temperature is higher than 200°C. This pair remains stable at high temperature and water has high latent heat than that of methanol and other refrigerant. The system fitted with this pair can be used for air conditioning application. The specific cooling capacities of these systems are not very high [Wang et al. 2010].

Anyanwu et al. 2005 evaluated the thermodynamic performance of different working pairs when designing a solar adsorption refrigerator. They found the best suitability of zeolite - water pair for air conditioning application and activated carbon-ammonia pair for refrigeration purposes.

2.2 Studies on Solar Photovoltaic Cooling Systems

A photovoltaic (PV) cell is basically a solid state semiconductor device that converts light into electrical energy. Small PV cells are typically used in wrist watches and calculators, whereas the larger ones are used for supplying power for industrial and domestic electrical appliances [Ullah et al. 2013]. Solar photovoltaic (SPV) cooling system from all solar cooling technologies have the widespread application due to its high power to weight ratio, simple , compact in size , less maintenance and no moving parts. The photovoltaic cooling system is mostly used to operate the refrigerator in the reviewed literature. Various researchers have operated the domestic refrigerator unit by photovoltaic power source and most of them used the vapour compression refrigerator. The studies of solar photovoltaic cooling can be grouped into two category numerical and simulation and experimental studies.

2.2.1 Modeling and simulation studies

Khelfaoui et al. 2000 performed simulation of the thermal part of the system using SIMULINK for the application of the system for preservation of perishable products in the isolated sanitary center. Financial analysis has been performed by using RET Screen for the autonomous PV/Diesel hybrid system installed in a bungalow for its use as low –cost electrification option at a tourist resort in Greece. [Bakes 2002]

Cherif et al. 2002 presents the performances, the simulated responses and the dynamic behavior of a photovoltaic (PV) refrigeration plant using latent storage. This approach utilizes a new storage strategy of standalone PV plants which substitute the battery storage with thermal, eutectic, latent or a hydraulic storage. The measurements and the evaluation of this battery less storage systems at several climatic conditions and under load disturbances allows us to evaluate the PV system reliability and to compare its performances with classic battery storage systems. The results of the analysis show that with good climatic conditions the storage starts at 10 a.m. and the stored energy is about W_{st}=705 Wh day-1. This energy can ensure autonomy of 1 day (with the same load).

Kannan et al.2009 have emphasized on the modeling approaches needed for meeting the targets of reduction in carbon-dioxide emission and have performed MARKEL modeling of the UK residential sector under long term decarburization scenarios.

Bilgili et al. 2011 presented the hourly simulation and performance of solar electric vapor compression refrigeration system has been proposed. In this paper photovoltaic panel area was evaluated for the various evaporator temperatures and in different months. The results show that for the evaporator temperature of -10°C the panel area required is 38.65 m^2 and for +10° C panel area is reduced to 18.69 m^2.

2.2.2 Experimental studies

Kattakayam et al. 1996 describes an autonomous power source for a domestic refrigeration unit which is powered by a field of photovoltaic panel backed-up by a generator set. There is a finite time delay between cut-out and cut-in of the compressor, changes in inverter’s design to meet the demands at the time of starting and at the time of running the motor.

Kattakayam et al. 2000, 2004 presents the cool-down, warm-up and steady state performance of a 100 W AC operated domestic refrigerator powered by a field of photovoltaic panels, a battery bank and an inverter. It is demonstrated that there is no degradation in the performance when a non-sinusoidal waveform AC source is used to run the refrigerator, although it may involve only a slight additional heating of the hermetic compressor. Thermal mapping of the temperatures at various stages on the refrigerator is provided for steady state, cool-down, warm-up, periodic opening of the door and ice making.

Kaplanis et al. 2006 describes the design and development phases to convert a conventional refrigerator to a solar powered one. A conventional refrigerator was chosen and some changes were introduced to reduce the cooling load and consequently the power required. Various tests were carried out to study the performance of the refrigerator components, especially on the compressor as well as the refrigerator as a whole. The modifications reduced the useful volume capacity by 30% which was the only drawback, while on the other hand this modification reduced heat loss, i.e. the cooling load considerably.

Modi et al. 2009 converted a 165 l domestic electric refrigerator to a solar powered one. In this paper they used 140Wp photovoltaic capacity and two 12V-135 Ah battery bank. It is the least possible configuration required for this converted system to work properly under normal condition. They suggest a larger panel size for sustainable system and more battery for backup. This system is not economically viable without initial financial incentives.

Ekren et al. 2011 presents the experimental performance evaluation of a PV powered refrigeration system. They show that a small household refrigerator with DC compressor can be operated by PV power without any inverter, thereby decreasing initial cost of the system. In this paper energy and exergy analysis was performed for the individual component and overall system for the no storage, low load, and nominal load and over load conditions. The highest coefficient of performance (COP) at no storage condition is found to 0.670 due to low compressor power consumption.

Ewert et al.2013 presents the field test result of battery free solar refrigerator in which the energy is stored in the form of thermal energy in the phase change material rather than the electrical energy in the battery. These units use 110 mm insulation to reduce the heat transfer. The cost of battery free unit (thermal storage and PV direct electronics) is much more than the conventional battery charged controller system. Once the market demand increases and mass production starts the cost will reduce in the future.

Ekren et al. 2013 presents experimental performance analyses of an alternative current (AC) and direct current (DC) compressors implemented in a 79 litre refrigerator. Experiments were carried out at continuously running (ON) and periodically running (ON/OFF) operation modes. The comparison showed that DC compressors can be much more efficient than AC compressors in refrigeration units. Experimental results demonstrate that the solar photovoltaic DC refrigerator can run normally and the running rate of the refrigerator is about 48.8% when it runs steadily with no-load and the average consumption of power is about 28.8W operated solely on solar energy with 24V photovoltaic panel.

Chien et al. 2013 performed the experimental study on absorption refrigerator driven by solar cells. The system was tested by the alteration of solar radiation in the range of 550-700W/m^2 as solar energy and 500ml water as the cooling load on ambient temperature, the refrigerator maintained the temperature of 5-8°C after 160 minutes. The coefficient of performance was calculated as 0.25.

The solar photovoltaic refrigerator, based on DC compressor, is also available in the market that reduces the loss of conversion from DC to AC. These refrigerator designs are specifically made for vaccine purpose and have very high level of insulation [http://www.sundanzer.com]. The availability of these types of refrigeration systems is quite less in India due to heavy price of DC compressor.

Some researchers have also carried out studies comparing solar photovoltaic cooling system with the solar thermal cooling systems through simulation. They operate air conditioner by means of PV power. [Hartmann et al.2011, Lazarin 2013, Eicker et al. 2014.] Table 2.3 shows the summary of solar photovoltaic cooling systems.

Table 2.4 Summary of solar photovoltaic cooling systems

Reference	Year	Application	Compression type	PV Area (m^2)	COP	Evaporator Temperature (°C)	Type
Kattakayam et al.	2000,2004	Refrigerator-165 liter	Compression-AC-100W	280W		-8 °C	Experimental
Cherif et.al	2002	Refrigerator	Compression-AC	200W		-15°C	Simulation
Kaplanis et al.	2006	Refrigerator	Compression-AC-	1870W		-8 °C	Experimental
Modi et al.	2009	Refrigerator-165 liter	Compression-AC-100W	140W	2.102	-4°C	Experimental
Bilgili et al.	2011	Refrigerator	Compression-AC	38.69 m^2		-10°C	Simulation
Ekren et al.	2011	Refrigerator-79liter	Compression-DC		0.670		Experimental
Hartmann et al.	2011	Air conditioning	Compression-chiller	0-36 m^2	3	6°C	Simulation
Ewert et al.	2013	Refrigerator-105 liter	Compression-AC	80-120 W		-4 °C	Experimental
Ekren et al.	2013	Refrigerator-79liter	Compression-DC-50W	80W	0.670	1-15°C	Experimental
Chien et.al	2013	Refrigerator	Absorption-AC		0.25		Experimental
Lazzarin	2013	Air conditioning	Compression chiller		3	6°C	Simulation
Eicker et al.	2014	Air conditioning	Compression chiller - 50kW	124 m^2	3.5	6°C	Simulation

2.3 Comparative Studies between Solar Thermal and Photovoltaic Cooling System

Elsafty et al. 2002 presented the economical comparison between a solar powered vapour absorption and vapour compression air conditioning system in the Middle East. The analysis was carried out for a 250 TR air conditioning system used for cooling a five floor student hospital in Alexandria, Egypt. They applied present worth comparison method and found that the total cost of vapour compression system was 11% lower than that of the single effect vapour absorption system. The double effect vapour absorption system has 30% lower cost than the vapour compression system.

Tsoutsos et al. 2003 presented the economic viability analysis of solar cooling technologies in Greece. They pointed out that the solar cooling technologies are not competitive compared with the standard cooling system at present energy prices. The solar cooling systems are presently not feasible without subsidy, mainly because of its high investment cost. However it is apparent that the cost of solar cooling technologies decreases as they enter the mass production.

Hartmann et al 2011 presented a comparison of two solar heating and cooling systems with respect to a reference system. The analysis is based on building simulations using the hourly heating and cooling load for two different locations in Germany and Spain. They found that for the large collector areas primary energy savings reaches 40 % and 60% for Freiburg (Germany) and Madrid (Spain). The solar electric (Photovoltaic) system outperforms the solar thermal systems in both current and future situation in terms of primary energy savings and economics.

Fumo et al. 2011 presented a comparative analysis of solar thermal and solar photovoltaic cooling system with reference to a standard air cooled vapour compression chiller operated by grid power. They presented the plots to evaluate the energy savings and emission reduction.

Lazzarin (2013) analyzed the solar thermal cooling system with the flat plate, evacuated tube collector and parabolic trough collector. The system are evaluated during sunny days and compared with the PV driven system and found that the PV driven system is now quite comparable.

Eicker et al. (2014) performed the primary energy analysis and economic evaluation of solar thermal cooling and solar photovoltaic cooling system, the comparison is made for three different climates in Palermo, Madrid and Stuttgart repectively. The same building area and geometry was used with a different user profiles and construction properties, consequently different cooling loads, in total 12 cases are taken into consideration. The primary energy savings reaches 50% with photovoltaic cooling systems while in the case of solar thermal system relative primary energy savings reaches 37% in Palermo, 36% in Madrid and 29% in the Stuttgart. Various literature conclude that the primary energy saving and, economic analysis are different for different climates, countries and electric prices.

2.4 Summary and Research gaps

The vapour absorption system is used in the field of refrigeration and air conditioning. Mostly the LiBr-water pair is used for air conditioning and NH_3-water pair is used for refrigeration and air conditioning both. However absorption based air conditioning system uses LiBr-water in the most cases due to its better suitability than ammonia-water. Lithium bromide system can work at low generator temperature that can be achieved by simple collectors. The evaporator temperature of LiBr-water system is high in comparison to ammonia water system because water works as refrigerant and restrict it for below 4°C application. The required collector area per kW of cooling is variable and depends on the climatic condition, cooling load profile and type of absorption system. The COP of chiller varies between 0.6-0.8.

Vapour adsorption systems are mostly used for the refrigeration especially ice production using activated carbon methanol as the working pair. Other working pairs also exist such as Activated carbon -ammonia, Zeolite-water, Silica-gel-water, etc. The solar COPs are very low and unable to produce continuous cooling.

Desiccant cooling systems are also used for providing conditioned air to spaces. These systems operate with evaporative cooler or with conventional vapour compression system. These have good capacity of handling the latent heat load and are most suitable for warm and humid climate. To handle the sensible heat load mainly in hot climates vapour compression system is coupled with it. The researchers have now started to pay more attention to the field of desiccant cooling system.

Solar photovoltaic cooling system is mostly used to operate small refrigerators in rural areas for preservation of food and vaccine. Various researchers investigated the domestic refrigerator by photovoltaic panel successfully and reported that it is not economically feasible when compared with the traditional vapour compression system. There are a very few attempt to investigate performance of air conditioner system through PV route, consequently very few paper present comparison of solar thermal and photovoltaic cooling systems technically and financially, though it has been reported photovoltaic system has the higher primary energy savings.

The literature also reveals that the performance of the system very significantly depends upon the climatic conditions and cooling load profiles. Parametric studies are therefore necessary to find out the system performance in different climates and with different cooling load profiles. It would for also be important to identify policy measures required to push most suitable option of solar cooling systems.

2.5 Area Identified for Further Research

Through study of the available literature, following potential areas were identified:

- There are very few studies for solar photovoltaic air conditioning systems.
- Solar photovoltaic cooling systems working through different types of PV cell technologies such as poly or thin film cells are not studied so far.
- There are very few studies that compared the solar thermal and solar photovoltaic cooling systems coupled with building load. For Indian climate, comparison of solar thermal and photovoltaic cooling system is not studied.

To fulfill the above the research gap the following objectives are defined

1. Comparative parametric study of small scale solar cooling systems using Solar Thermal (vapour absorption) and Solar Photovoltaic routes. Parameters to be considered are e.g. Area of absorber, Intensity of solar radiation and Climate zone.
2. Techno-Economic Comparison of Solar Thermal (vapour absorption) and Solar Photovoltaic Cooling Systems.

CHAPTER 3: MATERIALS AND METHODS

In this chapter the methods and material used for this research are described.

3.1 Description of Methodology

The whole research is divided into three phases. First phase is related to defining a building for carrying out the analysis. The building is divided into five zones and has a floor area of 225 square meters. The building geometry is developed in the Google Sketch up and imported in the TRAN-Build software. Parameters such as construction detail, occupancy, lighting load, ventilation, infiltration are defined as per Energy Conservation Building Code (ECBC) that is the national code for defining minimum efficiency of commercial buildings in India. The cooling load of the building is determined by using TRNSYS (software for transient simulation). The TRNSYS program provides the hourly cooling load of the building with break up as sensible cooling load and latent cooling load. Details of heat gain, w.r. t. source, such as wall conduction, reflection, direct solar heat gain etc are also available as output. The building cooling load can also be taken as zone wise.

In the second phase according to the cooling load of the building the component sizing for solar thermal cooling system and solar photovoltaic cooling is carried out. The building simulation of solar thermal cooling system is done in the program TRANSOL 3.1 (software for simulating thermal solar cooling systems) by taking suitable component and their size. The simulation of solar photovoltaic cooling system is done in the program TRNSYS. Based on the results given by the program's key parameters, solar fraction, primary energy savings, electrical (Grid) COP and paybacks are calculated for both types of cooling systems (Key parameters defined in section 3.7).

Finally in the last phase the techno-economic comparison is made for both types of cooling systems with respect to solar fraction, primary energy savings and paybacks. Fig 3.1 shows the complete structure of this research-

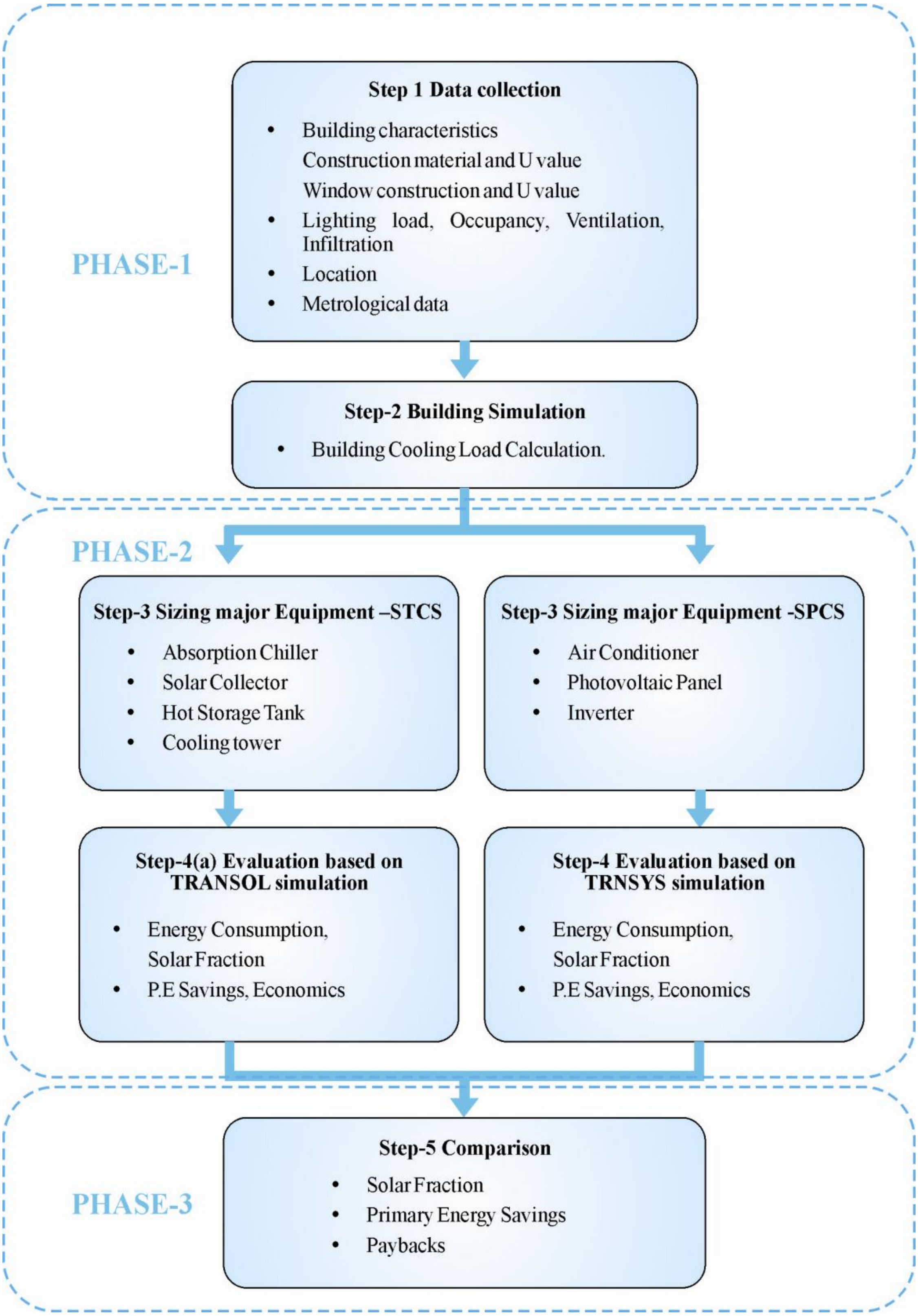


Fig.3.1 Methodology of research work

3.2 Simulation Tools

3.2.1 TRNSYS v 17

TRNSYS (TRaNsient SYstem Simulation) provides full and extendable simulation atmosphere for the transient simulation of systems including buildings located in different zones. It is used to authenticate new energy concepts from domestic hot water systems to the design and simulation of buildings and their machinery including control strategies as well as inhabitant behaviour, renewable energy systems (, solar, photovoltaic, wind hydrogen systems) etc.

The DLL (Dynamic Link Library) based design in TRNSYS allows users and third-party developers to easily add custom component models using all common programming languages (C, C++, PASCAL, FORTRAN, etc.). TRNSYS projects are formed by connecting components symbolically in the Simulation Studio. Mathematical models are used to describe the components.

TRNSYS components are often referred to as Types (e.g. Type 1 is the solar collector). The Multi-zone building model is known as Type 56. These Types are divided into groups; each one has number of Types that represent specific applications. TRNSYS consists of suite of programs. In this thesis, only two of these programs have been used; TRNSYS simulation studio and TRNBuild for Multi-zone building model [A TRaNsient simulation Program Volume-1, 2009].

A TRNSYS project is typically set up by linking components graphically in the Simulation Studio. Mathematical models are used to describe the components in the TRNSYS simulation program and have a set of identical proforma in the simulation studio. The proforma has a black-box description of a component: inputs, outputs, parameters, etc. [A TRaNsient simulation Program Volume-1, 2009].

The TRNSYS Suite

TRNSYS consists of a suite of programs: The TRNSYS simulation Studio, the simulation engine (TRNDll.dll) and its executable (TRNExe.exe), the Building input data visual interface (TRNBuild.exe), and the Editor used to create stand-alone redistributable programs known as TRNSED applications (TRNEdit.exe) [A TRaNsient simulation Program Volume-1, 2009].

The TRNSYS Simulation Studio

The main visual interface is the TRNSYS Simulation Studio (formerly known as IISiBat). This is used to create projects by drag-and-dropping components to the workspace, connecting them together and setting the global simulation parameters (Fig.3.2). The Simulation Studio creates the TRNSYS saves the project information in a Trnsys Project File (*.tpf). When run a simulation, the Studio also creates a TRNSYS input file (text file that contains all the information on the simulation but no graphical information) [A TRaNsient simulation Program Volume-1, 2009].

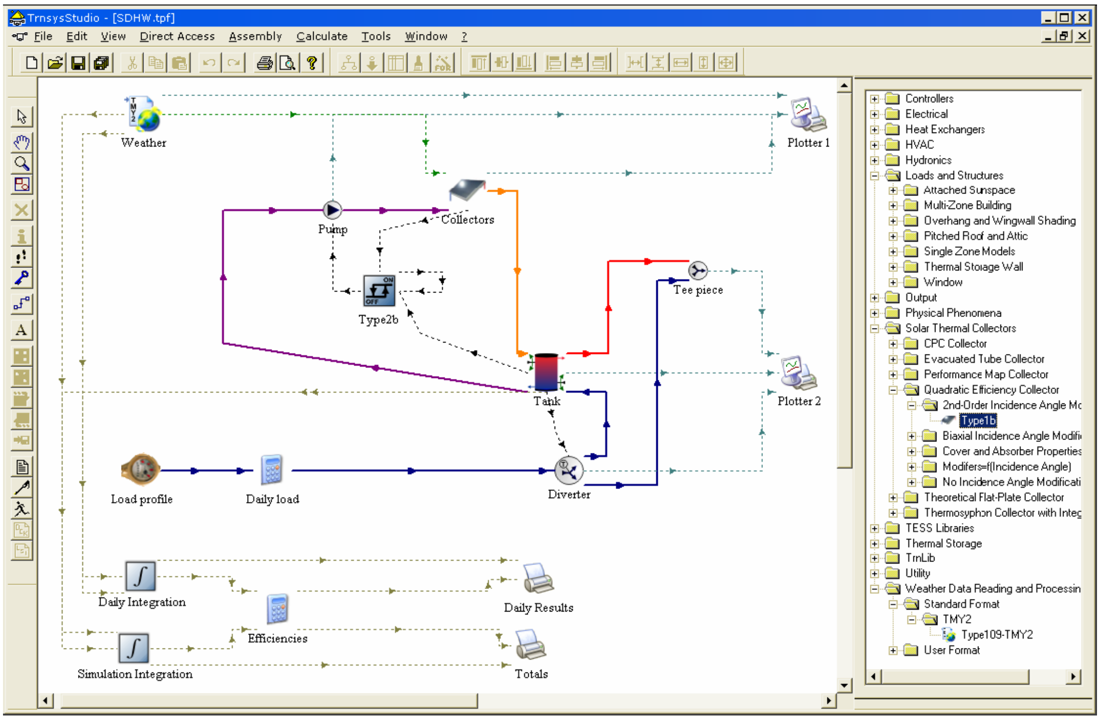


Fig.3.2 Example of domestic hot water system

The simulation Studio also includes an output manager to control which variables are integrated, printed and/or plotted, and a log/error manager. It can also perform many additional tasks: Generate projects using the "New Project Wizard", generate a skeleton for new components using the FORTRAN Wizard, view and edit the components proformas (a proforma is the input/output/parameters description of a component), view output files, etc. [A TRaNsient simulation Program Volume-1, 2009].

The TRNSYS Simulation engine

The simulation engine is programmed in FORTRAN and the source is distributed. The engine is compiled into a Windows Dynamic Link Library (DLL), TRNDll. The TRNSYS kernel reads all the information on the simulation (which components are used and how they are connected) in the TRNSYS input file, known as the deck file (*.dck). It also opens additional input files (e.g. weather data) and creates output files. The simulation engine is called by an executable program, TRNExe, which also implements the online plotter, a very useful tool that allows viewing a number of output variables during a simulation.

The online plotter provides some advanced features such as zooming and display of numerical values of the variables at any time step, as shown in the zoom part of fig. 3.3.

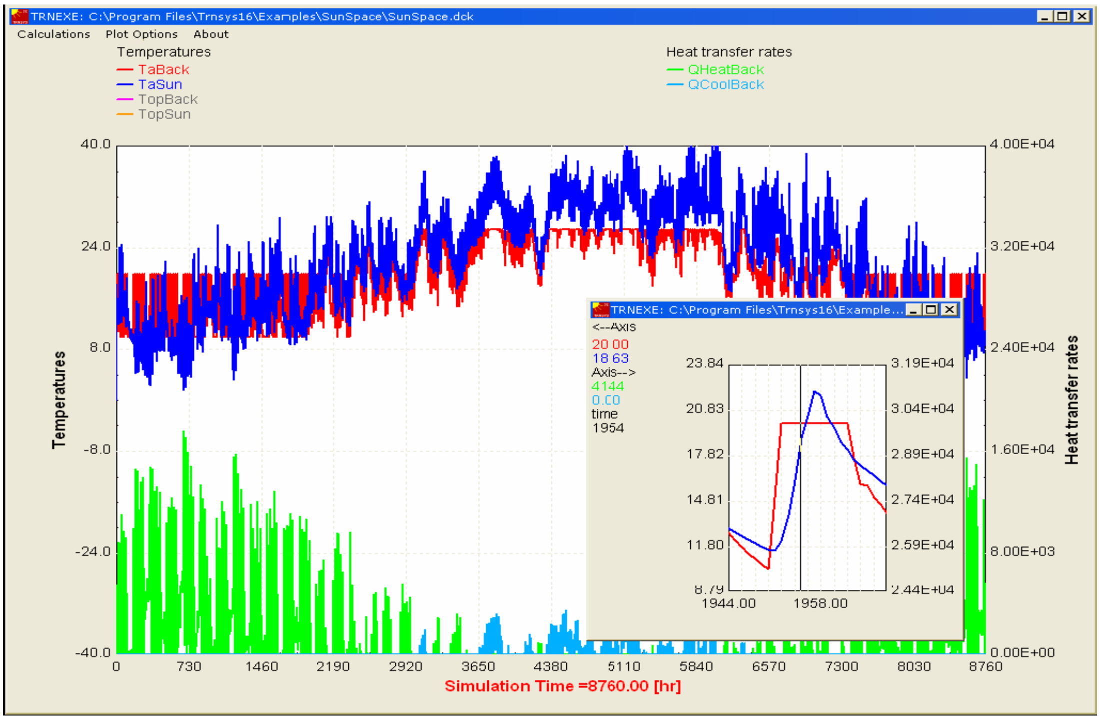


Fig. 3.3 Online plotter in TRNExe

The Building visual interface

TRNBuild (formerly known as Prebid) is the tool used to enter input data for multi zone buildings. It allows specifying all the building structure details, as well as everything that is needed to simulate the thermal behavior of the building, such as windows optical properties, heating and cooling schedules, etc. (Fig. 3.4). TRNBuild creates a building description file (*.bui) that includes all the information required to simulate the building [A TRaNsient simulation Program Volume-1, 2009].

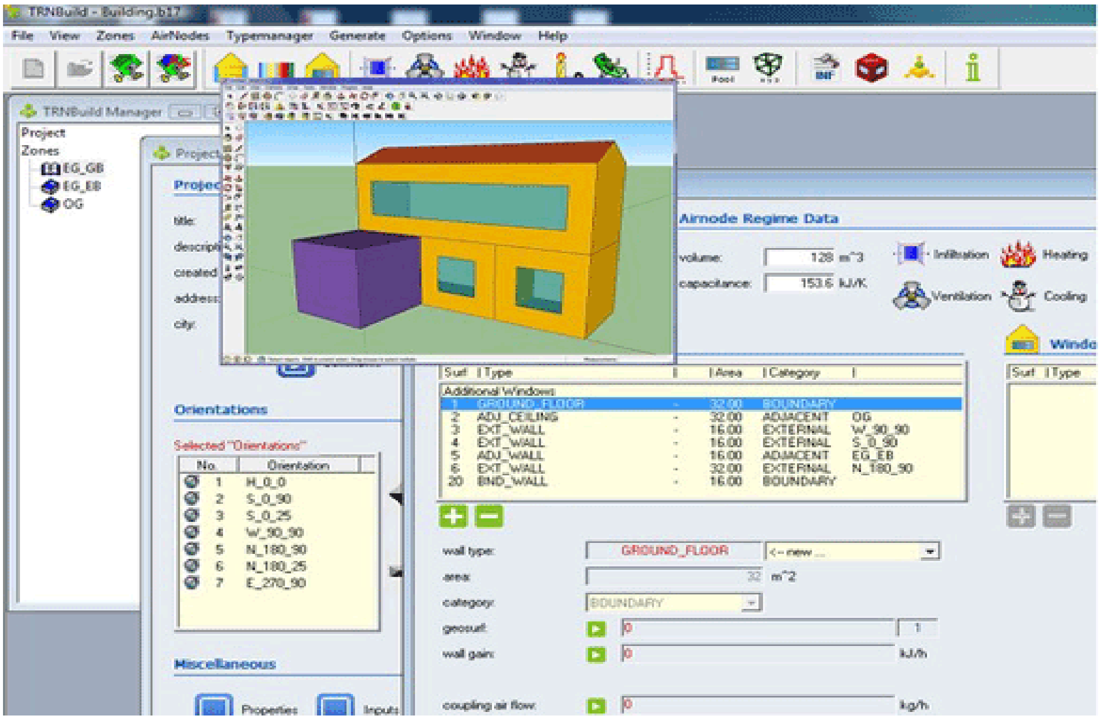
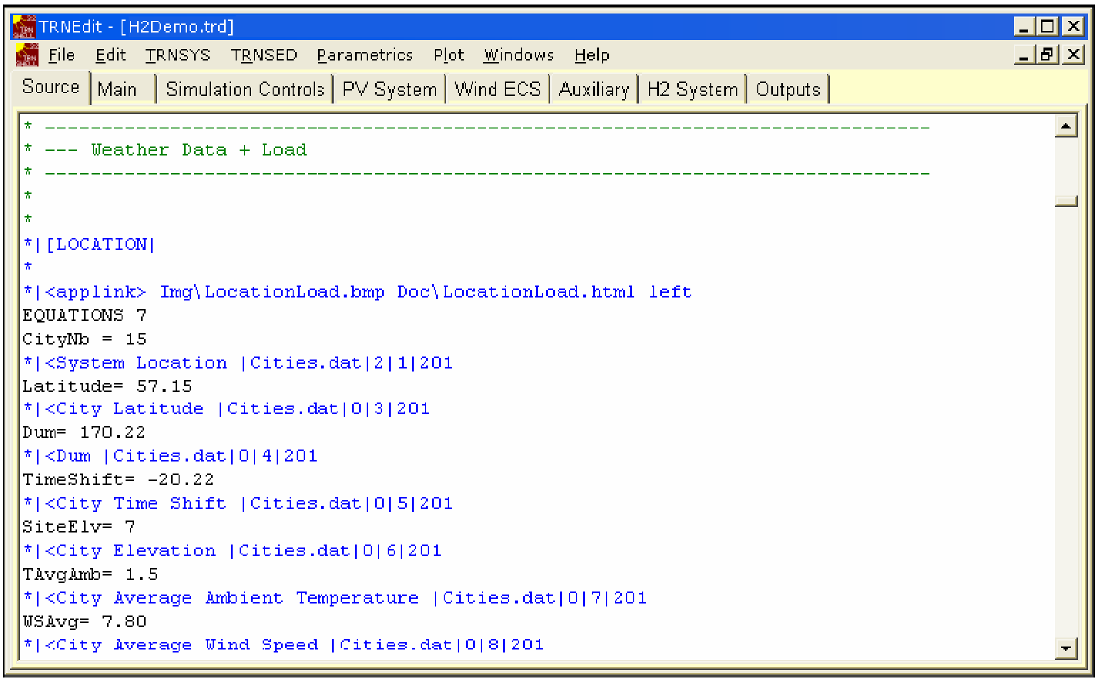


Fig. 3.4 TRNBuild

TRNEdit and TRNSED applications

TRNEdit is a specialized editor that can be used to create or modify TRNSYS input files (decks). TRNEdit can be used to create redistributable applications (known as TRNSED applications). Those executables can be freely distributed to end-users who do not have a TRNSYS license in order to offer them a simplified simulation tool (Fig.3.5). The distributable includes a dedicated visual interface designed by adding special commands to the TRNSYS input TRNSYS 17 – Getting Started **1–12** file. Advanced features, such as multiple windows (tabs) and clickable pictures, have been added in TRNSYS 17[A TRaNsient simulation Program Volume-1, 2009].



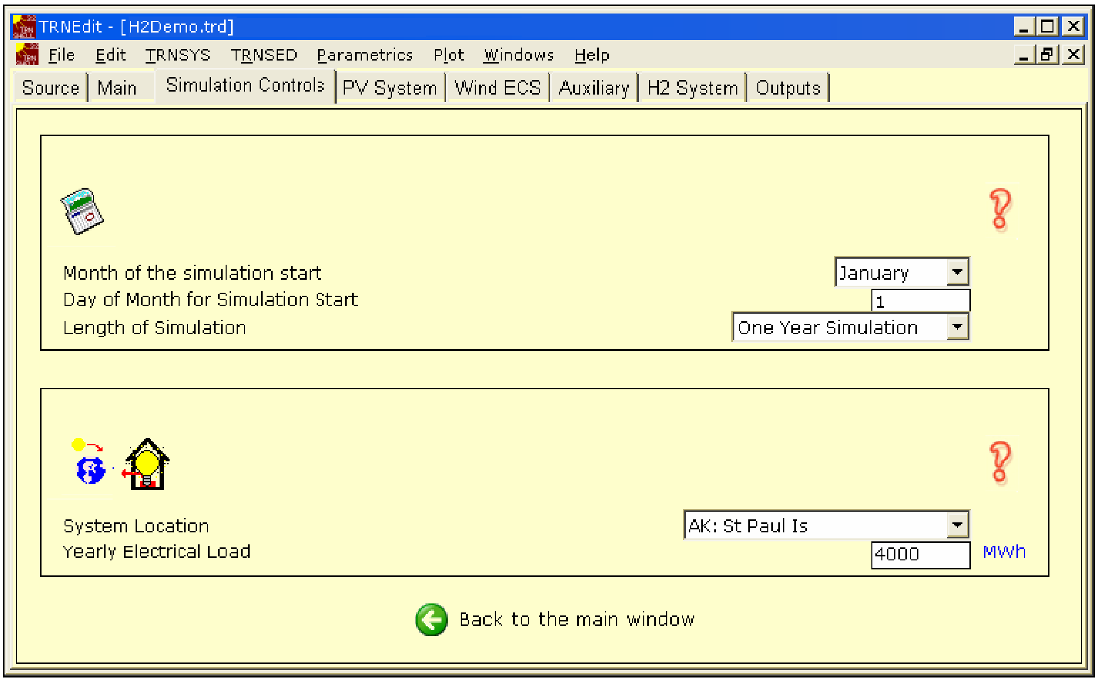


Fig. 3.5 TRNEdit – Tabbed view to design TRNSED applications

TRNSYS add-ons

TRNSYS offers a broad variety of standard components, and many additional libraries are available to expand its capabilities:

- TRNLIB: sel.me.wisc.edu/trnsys/trnlib (free component library)
- TRANSSOLAR libraries: www.transsolar.com
- TESS libraries: www.tess-inc.com.

3.2.2 TRANSOL PRO v 3.1

TRANSOL is a tool for the design and prediction of the behaviour of solar thermal energy installations. It was developed by CSTB (Canadian software testing board) and AIGUASOL (a self-managed cooperative company that offers engineering and energy consulting services). The tool is based on dynamic simulations (calculation with time steps of one hour or less) and it has been developed with TRNSYS (TRaNsient Systems Simulation Program) simulation tool. In TRANSOL we can select up to 35 basic configurations of solar thermal systems from which the system for cooling SCH601 is chosen in the present work.

This program works with meteorological weather data with which the heating and cooling energy demands are generated based on the building model. In this present work the cooling load is calculated by the TRNSYS program and couple to the model SCH601 in the TRANSOL program.

3.3.3 EnergyPlus v 8.1

The Energy Plus program that combines the best capabilities and features from BLAST and DOE–2 along with new capabilities to calculate the energy required for heating and cooling a building using a variety of systems and energy sources. In BLAST or DOE-2 the building zones, air handling systems and central plant equipment are simulated sequentially without any feedback from one to the other. This sequential simulation starts with the zone heat balance that updates the zone conditions and determines the heating/cooling loads at all-time steps. This information is fed to the system simulation module to calculate heating and cooling system and plant and electrical system response without feedback [Drury B. Crawley, 2001].

Energy Plus is well-organized, integrated modular structure that work together to facilitate adding features and links to other programs. This integrated simulation helps to overcome the most serious deficiency of BLAST and DOE–2 simulations that is inaccurate space temperature predication due to lack of feedback from the HVAC module on meeting loads. Accurate prediction of zone condition is necessary to system size, plant size, occupant comfort. Integrated simulation also allows users to evaluate a number of some of the more important include realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and inter-zone airflow. Feedback from the building systems simulation module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures and humidity if necessary[Drury B. Crawley, 2001].

EnergyPlus Structure

EnergyPlus has three basic components

- Simulation manager,
- Heat and mass balance simulation module, and
- Building systems simulation module

EnergyPlus is an integrated simulation. This means that all three of the major parts, building, system, and plant, must be solved simultaneously.

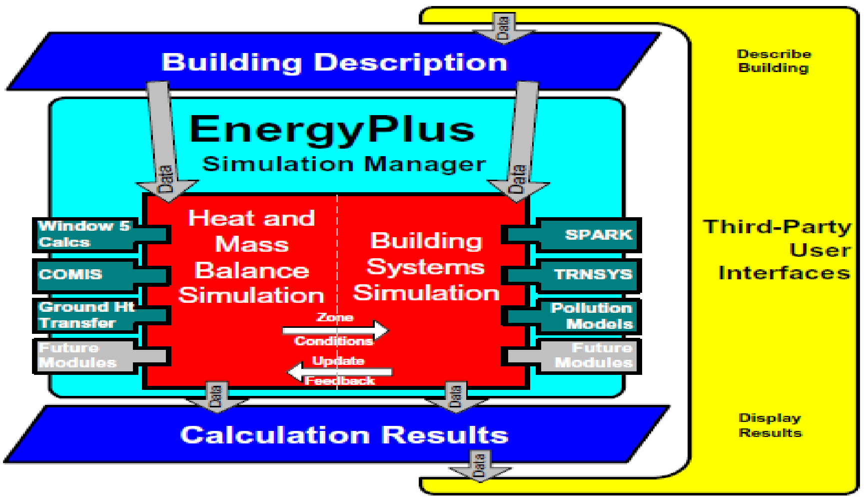


Fig.3.6 Overall EnergyPlus Structure (Drury B., 2001)

Simulation Manager

The Simulation Manager controls the interactions between all simulation loops from a sub-hour level up through the user selected time step and simulation period as shown in Fig3.6. Actions of individual simulation modules are directed by the simulation manager, instructing simulation modules to take actions such as initialize, simulate, record keep, or report. The simulation manager controls the entire simulation process.

Heat and Mass Balance Simulation

Fig.3.7 shows the structure of the EnergyPlus integrated solution manager that manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager. The surface heat balance module simulates inside and outside surface heat balance, interconnections between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer (water vapor) effects. The air mass balance module deals with various mass streams such as ventilation air exhaust air, and infiltration. It accounts for thermal mass of zone air and evaluates direct convective heat gains.

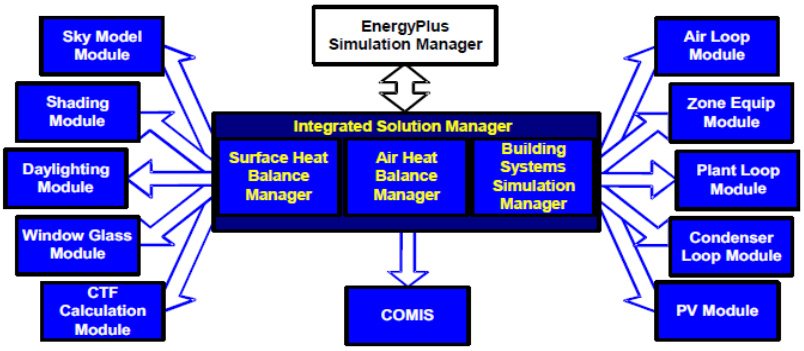


Fig.3.7 Integrated Simulation Manager (EnergyPlus, 2012)

Three categories of heat balances include outside surface heat balances, inside surface heat balances, and inside air heat balances shown in Fig.3.8.The heat balance approach would apply a control volume at an infinitesimally thin layer at both the inside and the outside surface for and balance the thermal forces. In each type of heat balance, the end result is the calculation of a temperature at which all of the thermal forces balance either a surface temperature or the temperature of the air within the control volume. The end result of each type of heat balances is the calculation of a temperature at which all of the thermal forces balance either a surface temperature or the temperature of the air within the control volume [Yaseen K 2014].

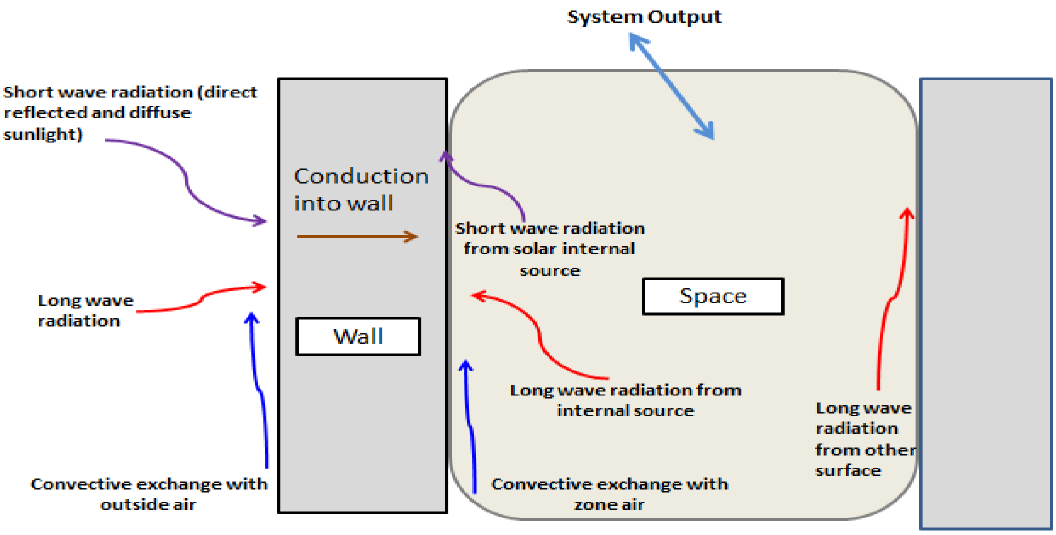


Fig.3.8 Heat balance Phenomenon of EnergyPlus [Yaseen 2014]

Building Systems Simulation Manager

The Building Systems Simulation Manager (Fig 3.9) is called when heat balance simulation is completed. This controls the simulation of HVAC and electrical systems, equipment and components and updates the zone-air conditions. Building systems simulation manager handles communication between the heat balance engine and various HVAC modules and loops, such as coils, boilers, chillers, pumps, fans, and other equipment/components.

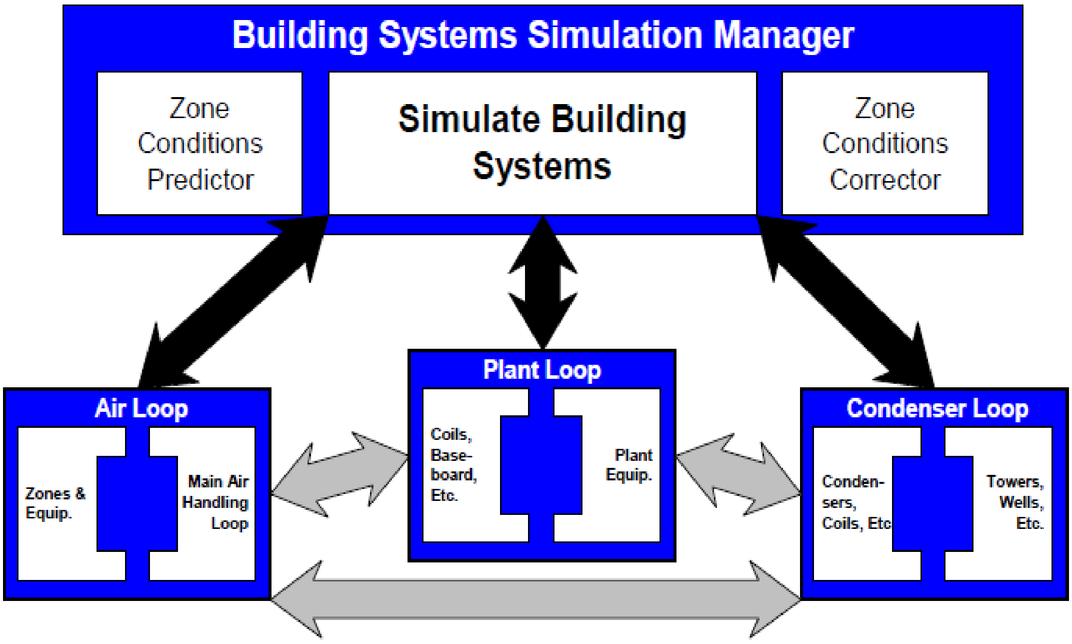


Fig3.9 Building System Simulation Manager (EnergyPlus 2012)

3.3 Description of Building Coupled with Solar Air Conditioning.

The building being used in this research work is an office square shape building with square envelope of 15 m length and 15 m width. The height of the building is 3.5 meters and total floor area is 225 m^2. Building is divided in the five zones in a typical perimeter-core pattern. Each perimeter zone is having depth of 3.6 meter as has been used in several other studies [Rajput et al. 2014, Gupta et al 2014].The entire building is used for office purpose in the day time only and whole area is conditioned. Windows on all four sides together constitute a window to wall ratio (WWR) of 26%. The detail dimension of Building is shown in the table 3.1 and in the fig.3.10.

Table 3.1 Building zone area and WWR

S.No.	Zone	Zone Area	Window Dimension	Orientations	WWR
1	East Zone	41.04 m^2	14x1 m^2 , One	East	27%
2	West Zone	41.04 m^2	14x1 m^2 , One	West	27%
3	North Zone	41.04 m^2	6x2 m^2 , Two	North	23%
4	South Zone	41.04 m^2	14x1 m^2 , One	South	27%
5	Core Zone	60.84 m^2	-	-	-

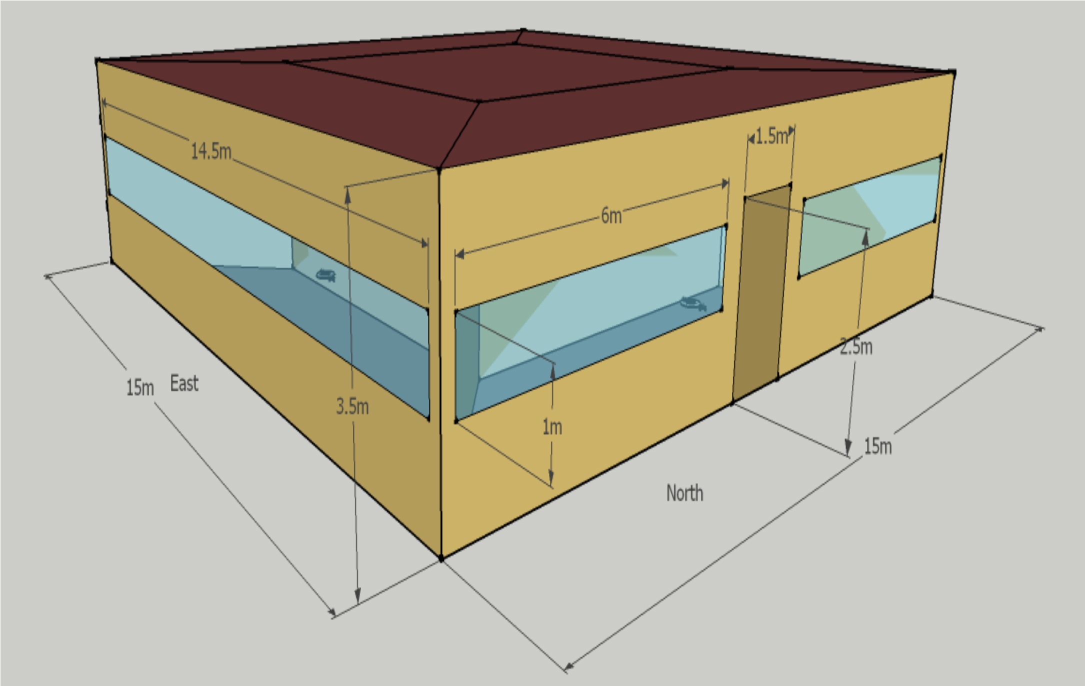
3.3.1 Building Envelope

Building envelope consists of the parts of building that separate the controlled indoor environment from the uncontrolled outdoor environment. It includes the walls, floors, roof and fenestration (windows, door) etc. Walls, roof and windows thickness and materials are selected such that the U-value of construction meets the Energy Conservation Building Code (ECBC) requirement. The main goal of ECBC is to provide minimum requirement for energy efficient design and construction of buildings and their systems. It provides the guidance to building owners, builders, engineers, energy consultants and designers how to comply with code. Table 3.2 shows the details of building construction of case building.

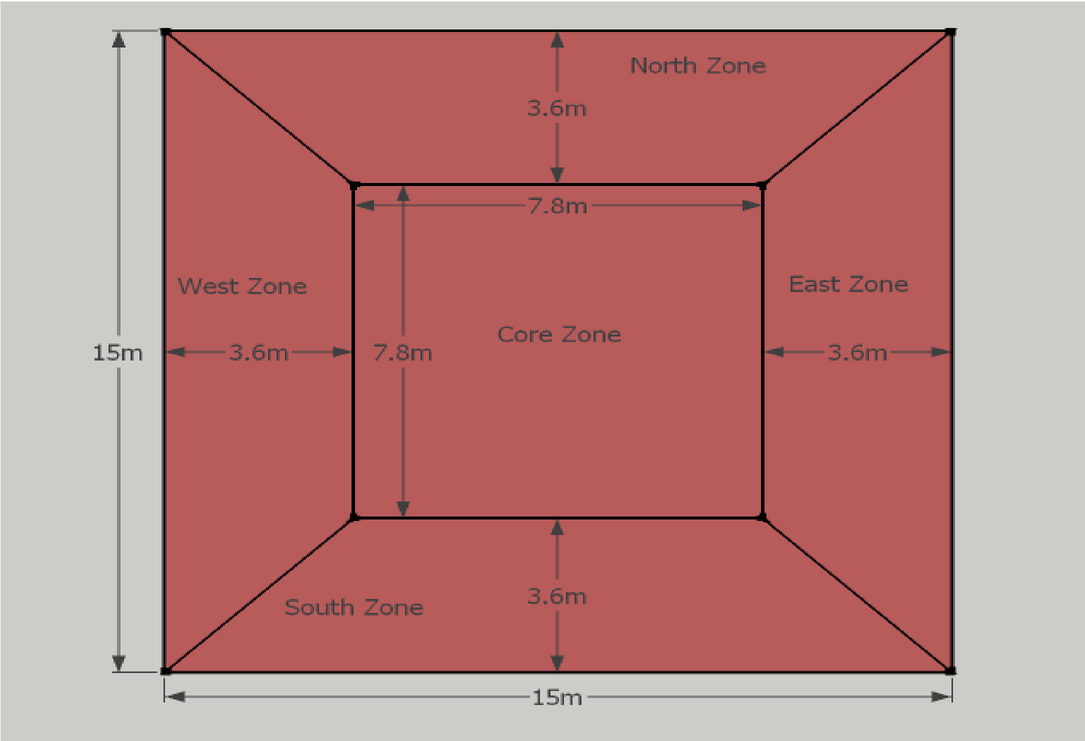
Wall is made of double brick of thickness 220 mm. The wall has cement plaster of 20 mm thickness on both sides. The inner side of the wall has 35 mm batt insulation. The total wall thickness is 0.295 m and U-value 0.433 W/m^2-K. The roof is made of 0.30 m concrete block from outside having the total area of 225 m^2. It has 30 mm cement plaster. The batt insulation material of 62 mm is placed on the inside surface of whole roof. The total roof thickness is 0.302 m and U-value 0.405 W/m^2-K. In the construction of the window double glass has been used. U-value and SHGC of glass is shown in Table 3.2. The properties of materials used in the construction are shown in the appendix.

Table 3.2 Building construction details [ECBC 2009]

S. No.	Surface	Layers	Thickness	Total Thickness	U - Value (W/m^2-K)	Thermal Resistivity (m^2-K/W)
1	Wall	Cement Double Brick Cement Insulation	0.020 m 0.220 m 0.020 m 0.035 m	0.295 m	0.433	2.30
2	Roof	Cast concrete Cement Insulation	0.300 m 0.030 m 0.062 m	0.302m	0.405	2.44
3	Window	Double glass			3.30	SHGC-0.25



(a)



(b)

Fig 3.10 (a) 3 D view of Building (b) Plan of Building

3.3.2 Building heat gains

Infiltration

Infiltration is the uncontrolled flow of outdoor air into a building through cracks and other unintentional openings and through the normal use of exterior doors for entrance and egress purposes. Infiltration is also known as air leakage into a building. (The Handbook of Fundamentals, 2009) Here, an infiltration rate of 0.2 air change per hour (ACH) has been taken for the building [Eicker et.al].

Ventilation

Outdoor air often termed as fresh air is required even inside the conditioned buildings to dilute as well as to remove indoor air contaminants. The exchange of outdoor air with the air inside the building is termed as ventilation. Here the fresh air requirement is calculated using ASHRAE standard 62.1-2004. The calculation of ventilation rate is described in Appendix.

Internal gains

The source of internal gains comprises of people, lighting and equipment loads in the building.

People: The person inside the building gives off heat and moisture from their different activities. This sensible and latent heat gain constitutes a large fraction of the total loads. In TRNSYS, sensible heat load and latent heat load are defined as per the person's activity. Here the load is taken 100W for people seated in rest position in the office. Out of 100W sensible heat load is 60W and latent heat load is 40W. These values are according to the ISO 7730. The occupancy in core zone is 8 people and in other zones 6 people in each as per the occupancy schedules.

Lighting and Equipment Loads: The lighting is one of the major space load components. The equipment inside the building consists of tube lights, computers, monitors, printers, etc. All these are heat sources inside the building and are the major space load components. The value for lighting power density (LPD) is taken as $10.8 W/m^2$ and equipment power density $11 W/m^2$ is taken.

Schedules

The building is used for office purpose and operating according to weekly schedule. There are separate schedules for workdays and weekends. Monday to Friday come in the workdays from 9 AM to 6 PM, Saturday and Sunday are holidays and termed as weekends. The lighting, equipment loads and air-conditioning schedules are according to workdays. Table 3.3 shows the details of internal loads in building.

Table 3.3 Internal load on Building

S.No.	Component	Core Zone	East Zone	West Zone	North Zone	South Zone
1	Zone Vol.(m^3)	212.94	143.64	143.64	143.64	143.64
2	Infiltration (ACH)	0.2	0.2	0.2	0.2	0.2
3	Ventilation(ACH)	0.73	0.79	0.79	0.79	0.79
4	LPD(W/m2)	10.8	10.8	10.8	10.8	10.8
5	People(Nos.)	8	6	6	6	6
6	EPD(W/m2)	11	11	11	11	11
7	Schedule(Time)	0900-1800	0900-1800	0900-1800	0900-1800	0900-1800

3.3.3 Building cooling load analysis

The cooling load of the five zone building having a conditioning area of 225 m^2 is determined by using the TRNSYS program. From the building cooling model the cooling load can be determined partly by infiltration gain, ventilation gain, sensible gain and latent gain. The cooling load of the building can also be calculated zone wise by using the TRNSYS program.

Monthly peak cooling load analysis

The total cooling load of a building is the summation of infiltration, ventilation, solar gain through walls, windows and roof and internal load including occupant load. The infiltration load is due to cracks, fenestration in the walls and roof whereas ventilation load is due to fresh air supplied to the building. The person sitting inside the building adds heat through in the form of sensible and latent load. Lighting equipment is also responsible for the cooling load. The major part of the load is by solar gain through the walls and windows depending on the U-value of the construction and solar heat gain coefficient (SHGC) of glass. In this study the building load is calculated by using TRNSYS simulation program for four cities situated in four different climatic zones. Fig. 3.11 shows the monthly maximum cooling load of the building and it is clear from the fig 3.11 that the maximum cooling load for Ahmedabad is in April, for Bangalore and Chennai in May and for Delhi in June. Also in the composite climate (Delhi) the variation in the maximum cooling load throughout the year is very high whereas in the moderate climate (Bangalore) the cooling load variation is low in a year. According to the highest cooling load value in a year the capacity of cooling system is picked up for sizing of solar cooling system.

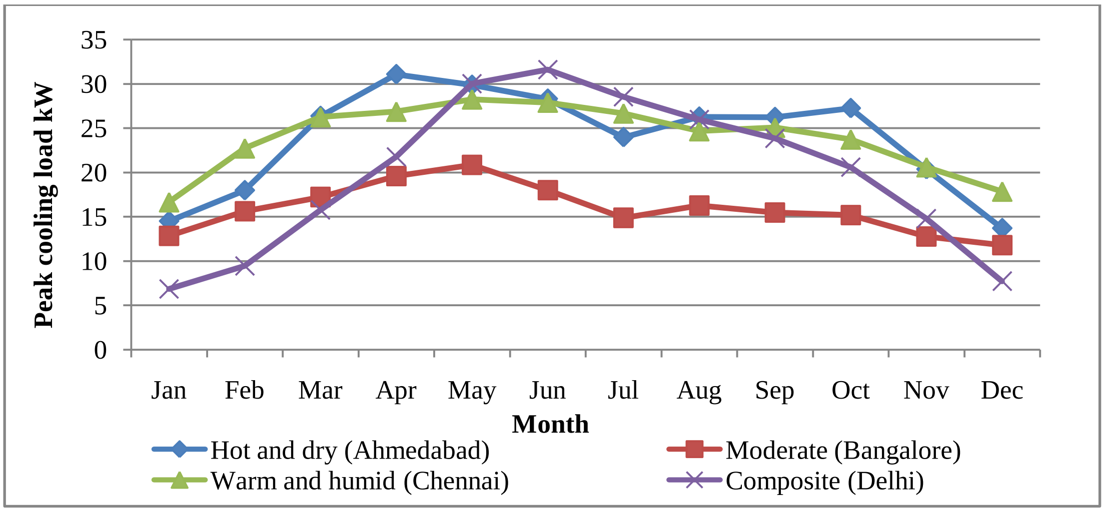
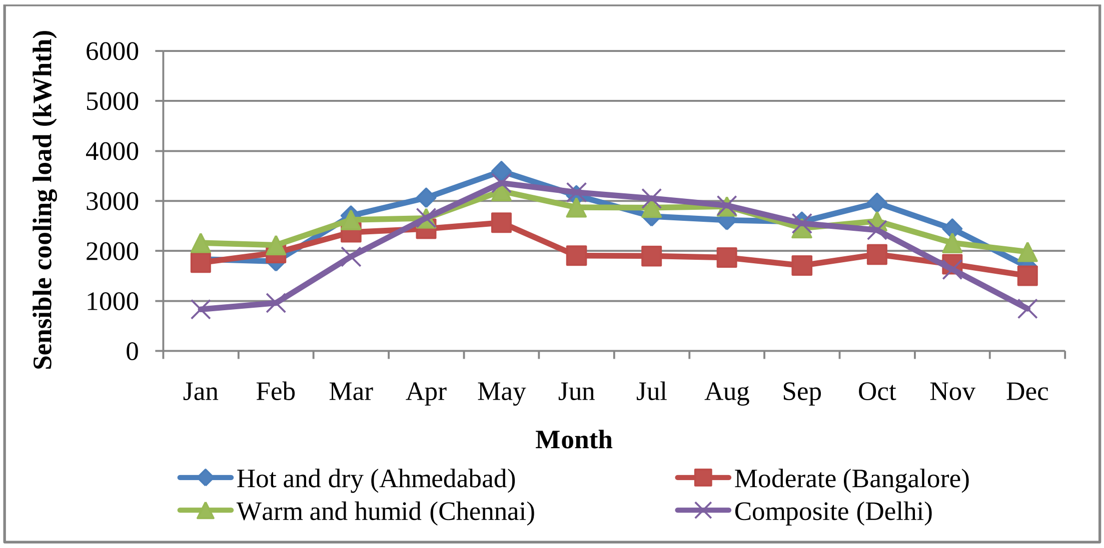


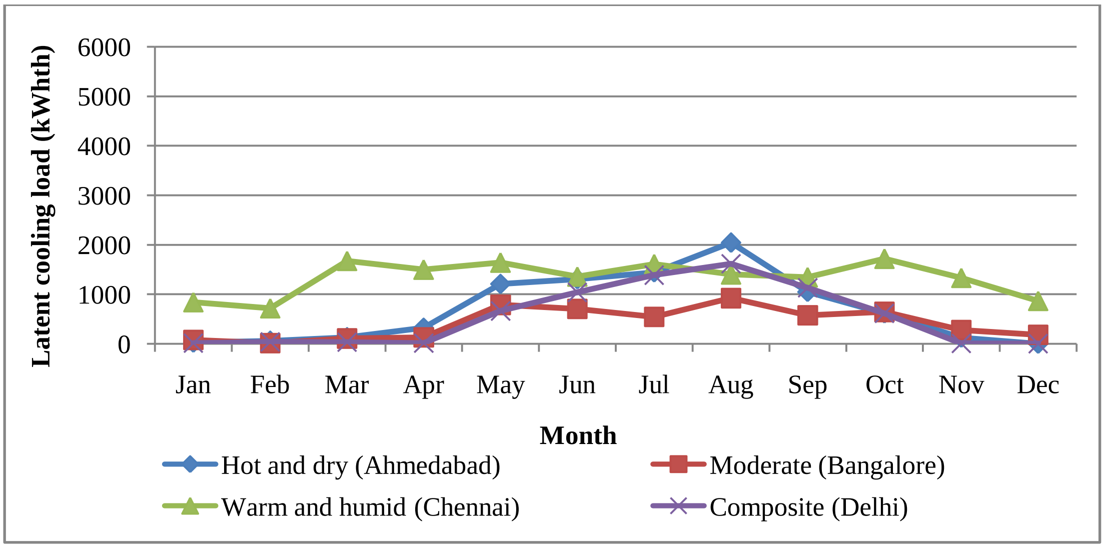
Fig. 3.11 Monthly variation of peak cooling load

Monthly latent and sensible cooling load analysis

Figures 3.12 (a), (b) and (c) show the monthly variation of latent, sensible and total cooling load for the different cities respectively. The sensible cooling load is very high in the summer season in all climatic zones except for the moderate climate when it is considerably low. In the winter month (Dec-Feb) the sensible cooling load is very low for the composite climate because in this season the ambient temperature is very low however in other climate it is slightly high. The latent load is very high for Chennai throughout the year because of the high humidity whereas in the other cities it is low except in rainy season from May to September. Fig. 3.12 also shows the variation of sensible and latent load for different climatic zones.



(a)



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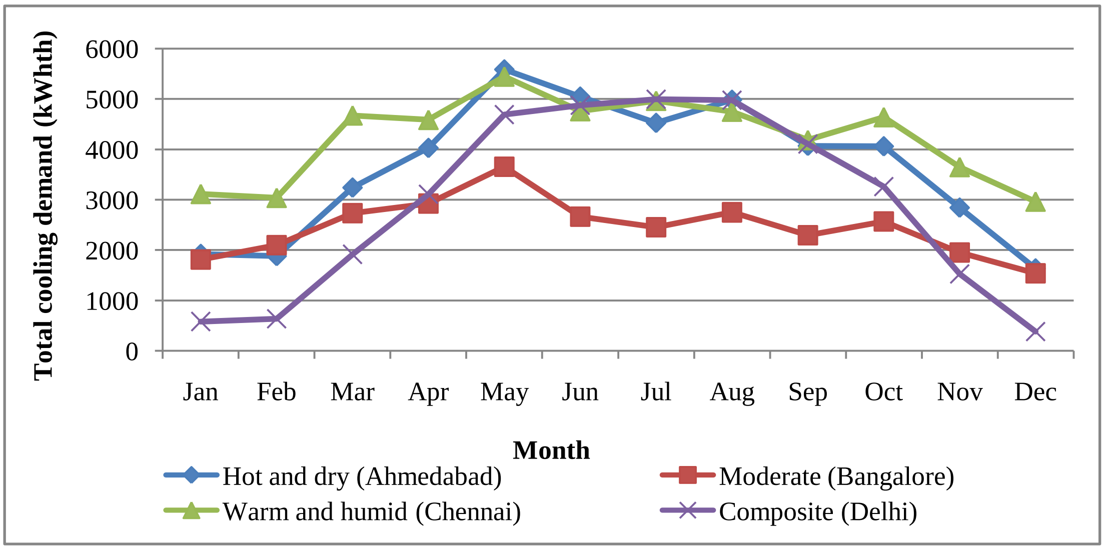


Fig. 3.12 Monthly cooling demand (kWh_{th}) (a) Sensible, (b) Latent and (c) Total

Monthly zone wise cooling load analysis

Fig.3.13 shows the zone wise total cooling demand of a building's conditioned area per square meter. It is clear that the annual cooling demand is lowest for core zone because not a single wall is directly exposed to the sun except the roof. Comparatively the cooling demand is higher for the South zone due to higher radiation in the South. East and West cooling demands are nearly the same for all climatic zones and in the North zone the cooling load is also lower than the East, West and South zone but higher than the core zone.

The total cooling demand is highest for the warm and humid climate (Chennai), due to high humidity resulting in the higher latent load. In the moderate climate (Bangalore) the temperature of the ambient is moderate throughout the year so the cooling demand is lowest. Hot and dry (Ahmedabad) and composite (Delhi) have the cooling demands in-between the above two climates.

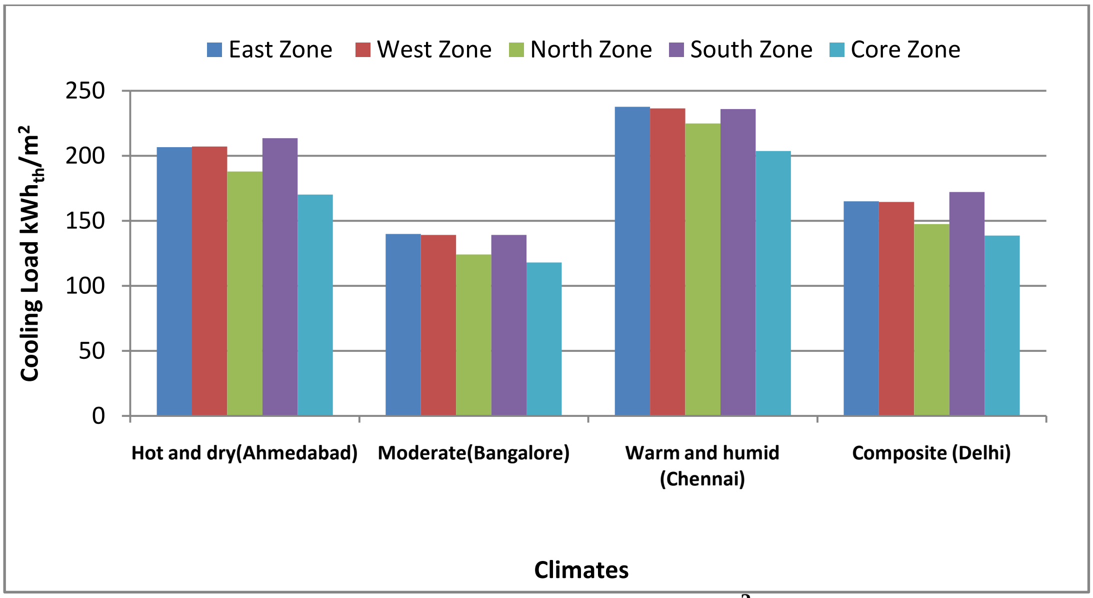


Fig. 3.13 Zone wise annual cooling load kWh_{th}/m^2 of conditioned area

Annual cooling load analysis

Fig. 3.14 shows the annual cooling demand and peak cooling load for different cities selected from different climatic zones. It is clear that the highest peak cooling load is 31.6 kW for composite climate (Delhi) and lowest 20.9 kW for moderate climate (Bangalore) while annual cooling load per square meter of building area is highest 226 kWh_{th}/m^2 for warm and humid climate (Chennai). This indicates that the peak cooling load may be higher for the composite climate (Delhi) 31.6 kW and hot and dry climate (Ahmedabad) 31.1 kW but the total cooling demand is higher for the warm and humid climate (Chennai) because the variation in the temperature throughout the year is higher in the composite climate (Delhi) and hot and dry climate (Ahmedabad) resulting in the peak load whereas in the warm and humid climate the latent heat load is much higher than others increasing the total cooling demand. Another reason for highest cooling energy demand in the warm and humid climate is the longer cooling period in a year. The annual cooling energy demand is 195kWh$_{th}$/m^{2,} 131 kWh$_{th}$/m^2, 226 kWh$_{th}$/m^2 and 156 kWh$_{th}$/m^2 for the hot and dry, moderate, warm and humid and composite climate respectively. The peak cooling load is 31.1 kW, 20.9 kW, 28.3 kW and 31.6 kW for the hot and dry, moderate, warm and humid and composite climate respectively.

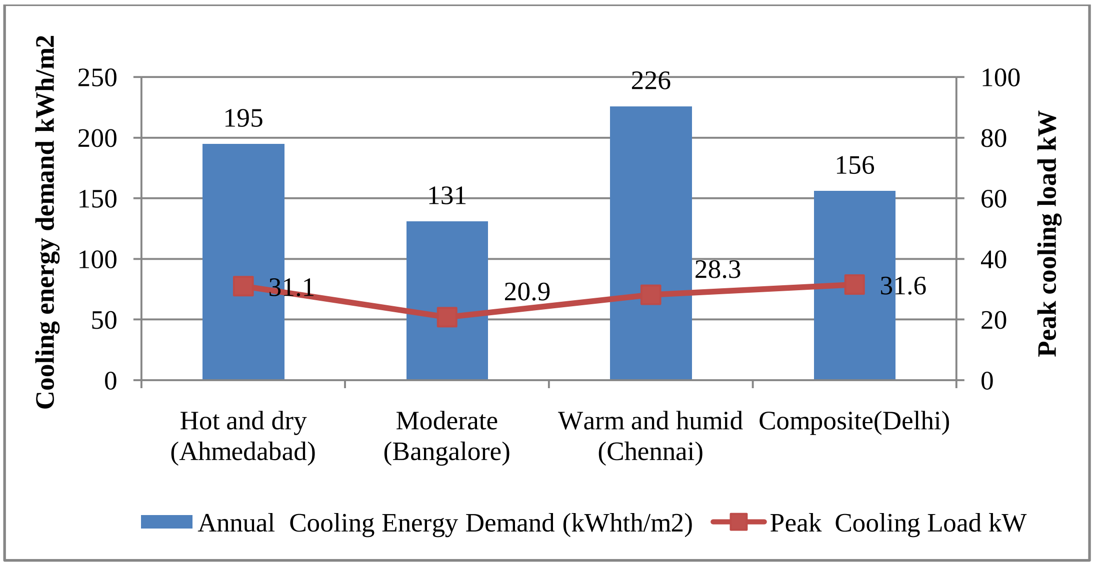


Fig 3.14 Annual cooling energy demand and Peak cooling load

3.4 Description of Analyzed Solar Thermal Cooling Systems

In the present work comparison of two small scale solar cooling systems is carried out using two different programs. The program TRANSOL EDU 3.1 is used for the simulation of a solar thermal cooling system and TRNSYS v-17 program is used for the simulation of a photovoltaic operated cooling system. The simulation is carried out for an office building used in day time only and which is considered to be in four climate zones in India an Asian country.

The solar thermal cooling system is simulated using a configuration SCH 601 from the program TRANSOL EDU 3.1 as shown in the fig 3.15. This configuration shows the complete heating, cooling and domestic hot water (DHW) application. In this study only cooling is considered for analysis purpose.

The solar analyzed thermal cooling system is composed of a solar collector field (Solar collector), hot storage tank (HST), cold storage tank (CST) and vapour absorption chiller (VAC). Three different types of collectors are considered in this study flat plate, evacuated tube and compound parabolic. The solar collector captures the energy from the sun and supplies energy to a hot storage tank through an external heat exchanger. Two pumps are used in the solar collector loop, one is to circulate hot working fluid from solar collector to heat exchanger, and another to circulate fluid between heat exchanger and hot storage tank. These pumps (P1, P2) are known as primary and secondary pump respectively and operated by control strategy depending on solar radiation intensity. The flow rate of pump is constant. The system stops the pumps if the temperature in the hot storage tank exceeds the maximum security value. A vapour absorption machine (VAM) is directly connected to the hot storage tank, this machine is turned on when cooling is required and the temperature of the solar tank is over a set point temperature [Bongs C.2009]. The heat coming from the absorber and condenser is released by cooling tower controlled by a variable frequency drive that increases energy efficiency and reduces electrical energy consumption. The cold water coming out from the evaporator of vapour absorption machine is stored in the cold storage tank (CST). An electrical operated compression cooling machine is used as a backup in order to cover complete cooling demand of the building. This compression based cooling machine is operated only when the cooling demand is in building and the temperature of the cold storage tank is below than the specified set point temperature. The main components of the solar thermal cooling system are described below.

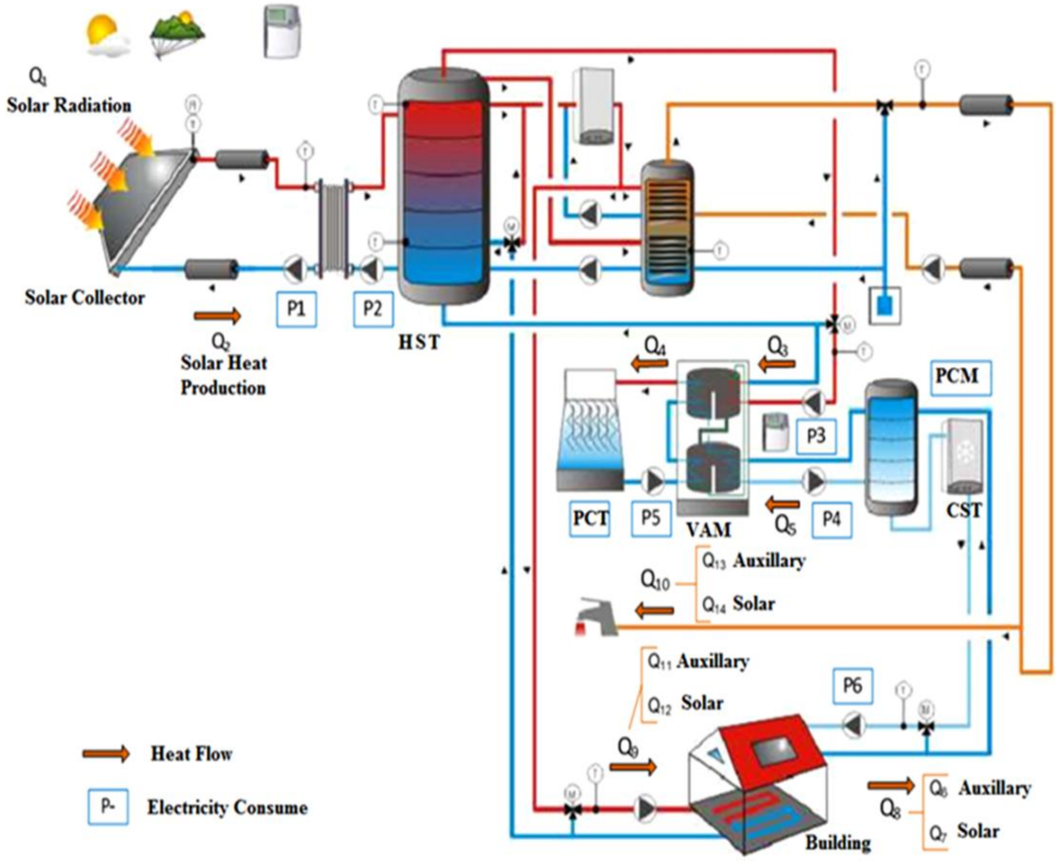


Fig 3.15 Solar thermal cooling system-SCH 601[TRANSOL]

3.4.1 Solar thermal collector

The solar collector is the device that converts solar radiation into thermal energy that drives a solar assisted air conditioning system. The central component in solar collector is the absorber. Here, the absorbed solar radiation is transferred in heat; partially this heat is transferred to working fluid inside the collector and remaining lost to the environment [Henning 2007].

Flat plate collector (FPC)

The flat plate collectors are usually designed for the application requiring up to 100°C temperature. They use both beam and diffuse radiation and are usually not provided with feature for tracking of the sun. They require low maintenance. Fig3.16 and 3.16 show the cross section and construction of a flat plate collector.

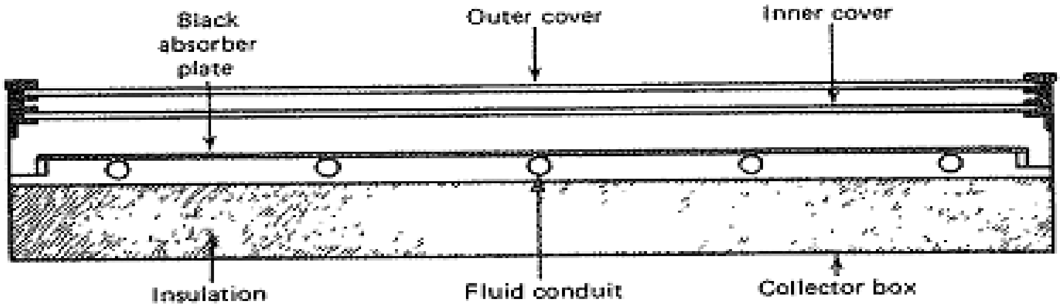


Fig 3.16 Flat Plate collector – Cross section [Duffie and Backman, 2006]

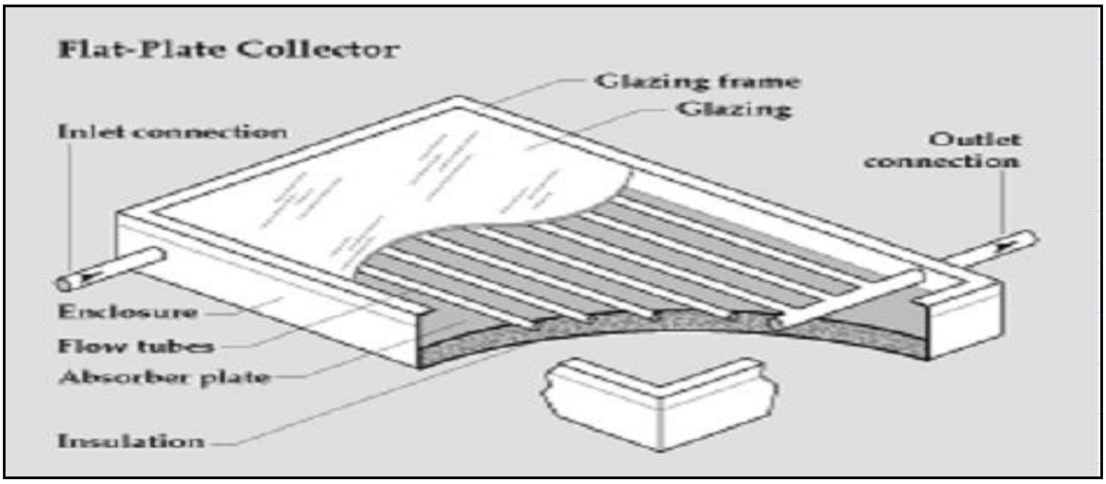


Fig. 3.17 Typical construction of Flat plate collector [Kalogirou 2004]

The useful gain of the collector is calculated using the following equation.

$$Q_{useful} = m^{*}C_p(T_0 - T_i) = AF_R[G(\tau\ \alpha) - U_L(T_{avg} - T_{amb})] \quad (3.1)$$

Where F_R is the collector heat removal factor, it is the ratio of the actual collector useful heat to that of the collector if it is at a uniform temperature equivalent to the inlet fluid temperature, and is given by

$$F_R U_L = \quad a_1 + a_2(T_{avg} - T_{amb}) \quad (3.2)$$

The efficiency of solar collector is given by [Henning 2007]

$$\eta = k(\Theta).\eta_0 - a_1.\frac{T_{avg} - T_{amb}}{G} - a_2.\frac{(T_{avg} - T_{amb})^2}{G} \quad (3.3)$$

Where

$k(\Theta)$ = Incident angle modifier η_0 = Optical efficiency

a_1 = Linear loss coefficient W/m^2-K a_2 = Quadratic loss coefficient W/m^2-K

T_{avg} = Average fluid temperature in the collector (̊C) T_{amb} = Ambient air temperature (̊C)

G = Incident global solar radiation on collector surface W/m^2

Evacuated tube collector (ETC)

The evacuated tube collector have the high strength and resistant to implosion which eliminates the convection losses by surrounding the absorber with a vacuum of the order of 10^{-4} mm of Hg. Fig 3.18 shows the typical construction detail of a typical evacuated tube collector. In this type the glass evacuated tube is used as a heat pipe, each tube consists of two glass tubes. The outer tube is made of extremely strong transparent borosilicate that is able to resist impact. The inner tube is also made of borosilicate glass, but coated with a special selective coating that enhances the heat absorption capacity and reduces the heat reflection properties. The air is evacuated from the space between the two glass tubes to form a vacuum which eliminates the conductive and convective heat losses [H.P Garg, 2000].

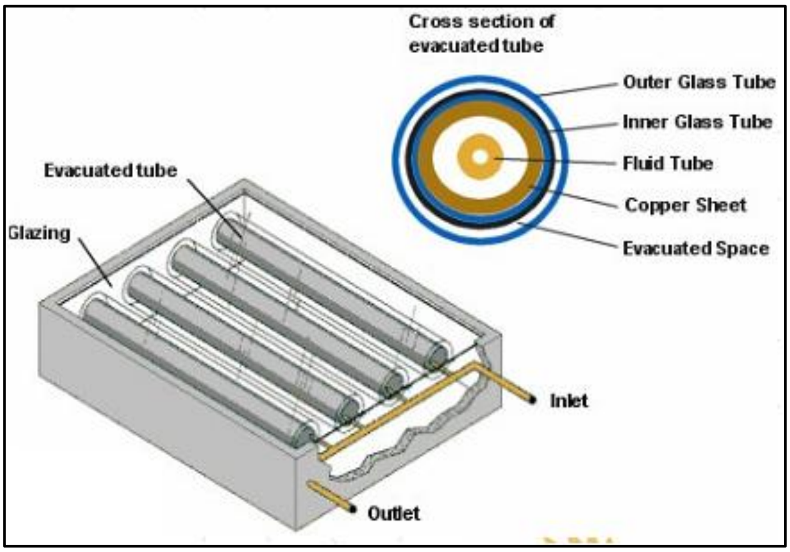


Fig. 3.18 Schematic diagram of an evacuated tube collector

Compound parabolic collector (CPC)

In the compound parabolic collector (CPC) the efficiency is increased by increasing the incident energy on the absorbing surface. This is achieved by use of reflective surfaces onto a suitable absorber/receiver placed at the focus of parabola. They collect beam, diffuse sky and ground reflected solar radiation. These collectors are used for heating of a liquid in the range of 50-110°C. These collectors have two orthogonal axes symmetry and are designed with acceptance angles greater than 30°C. Fig 3.19 shows the detail of the compound parabolic collector. The concentrator factor of CPC is less than 2. In this study the 70-110 m^2 collector area is selected [Henning H.M.2007]. The other parameters used for the different type of collector are listed in the table 3.4.

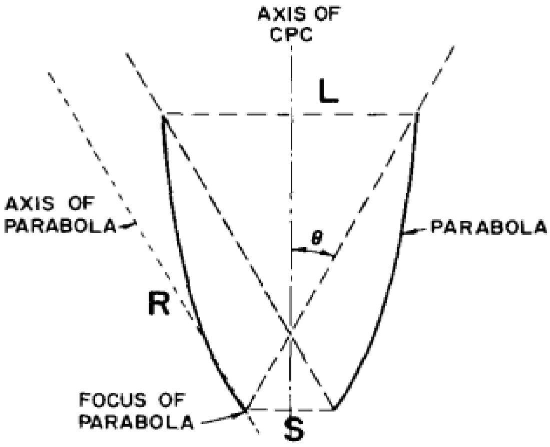
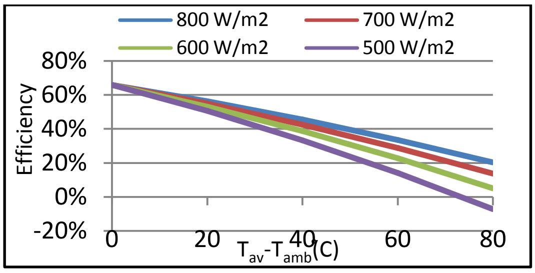


Fig. 3.19 Compound Parabolic Collector [Tiwari, 2011]

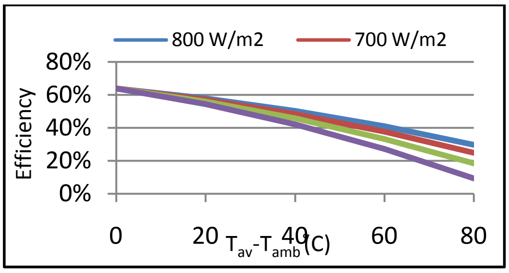
Table 3.4 Solar collector parameters used in simulation [TRANSOL]

S.No.	Type / Parameters	Flat plate collector	Evacuated tube collector	Compound Parabolic collector
1	Manufactured	Yazaki	Sungeosetz	Rittor Solar
2	Product	Y-2000	Sungeoset-SER	21 Star azzuro
3	Laboratory	CSTB	CSTB	CSTB
4	Zero loss efficiency (Conversion factor) η_0	0.733	0.710	0.550
5	Loss coefficient a_1 W/m^2-K	3.606	2.010	0.920
6	Loss coefficient a_2 W/m^2-K	0.120	0.0175	0.000
7	IAM	0.90	0.90	0.90
8	Height meter	1.730	1.935	2070
9	Unitary Area m^2	2.390	2.250	2.330
10	Qt l/h-m^2	72	72	72
11	Capacitance kJ/m^2-K	10.78	10.78	10.78

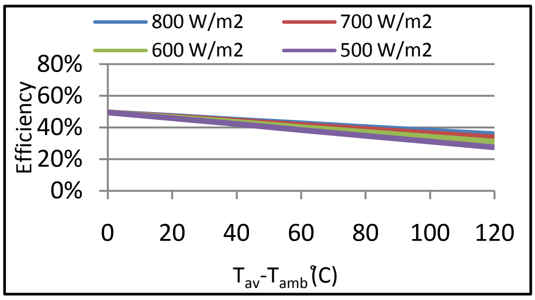
The collector efficiency curves are usually expressed as a function of the difference between average fluid temperature T_{avg} and ambient air temperature, T_{amb}. Using the equation 3.1, 3.2, 3.3 and parameters listed in the table 3.4 the efficiency curve have been drawn for the three types of collectors and these are shown in the fig 3.20.



(a)



(b)



(c)

Fig: 3.20 Collector efficiency versus the difference between the fluid average temperature and ambient air temperature for different incident solar radiation values (a) FPC (b) ETC(c) CPC the used collector parameter are taken from table 3.4

3.4.2 Solar heat exchanger

A solar heat exchanger (SHE) is employed between the solar collector and hot storage tank. A primary pump is used to connect the solar collector and heat exchanger. A heat transfer coefficient of 100 W/°C per meter square of collector area is considered in the present work [TRANSOL].

3.4.3 Hot storage tank

The hot storage tank (HST) is used to store the solar energy when the amount of solar collected energy is more than the application required and supplies the energy when the collected amount is inadequate. The hot storage tank provides a buffer stock between the solar collector and generator of absorption chiller and makes a system operation steadily [Mazloumi et.al, 2008]. For a common consumption profile, the solar storage should have a volume at least 50 times the collector area in m^2. In this study collector area is 70-110 m^2 so a hot storage tank of 5000 liter is selected.

3.4.4 Vapour absorption chiller

Fig 3.21(a) shows a schematic diagram of a solar thermal cooling system. Water is directly pumped to the solar collector where it is heated by the collected heat and transfers the heat to the hot storage tank. Heat energy from the storage tank is supplied to the generator of the absorption chiller. In the generator this heat is used to vaporize the refrigerant (water) from the LiBr-water solution and separates it from solution. Then the superheated vapour condensed in the condenser and heat is rejected to the environment by means of cooling tower. The condensed liquid refrigerant flows through an expansion valve to the evaporator where it absorbs the heat from the surrounding and produces cooling effect. The refrigerant (water) changes in the vapour phase and absorbed by high concentration solution coming out from the generator in the absorber. The absorbing process also librates heat and is rejected by cooling tower to the ambient. Finally low concentration solution is pumped through the heat exchanger to the generator.

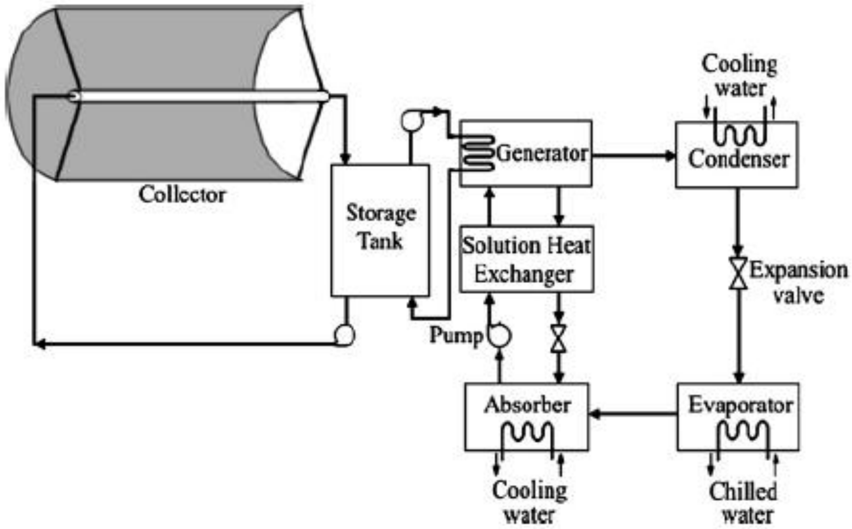


Fig 3.21(a) Schematic of solar vapour absorption cooling system [Mazloumi et.al, 2008]

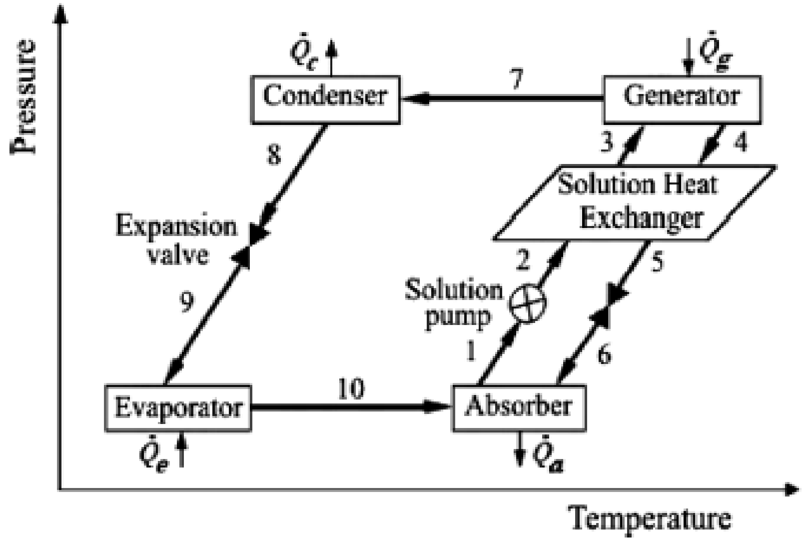


Fig 3.21(b) Pressure Temperature diagram [Mazloumi et.al, 2008]

The performance of an absorption cycle can be simulated well by a thermodynamic model. The pressure temperature diagram for the absorption cycle is shown in fig 3.21(b) in which the evaporator and absorber are at low pressure while the condenser and generator are at high pressure. The basic assumptions of a thermodynamic model of absorption cycle are [ASHRAE, 2009].

1. There are steady state conditions and the steady state refrigerant is pure water.
2. No pressure change except in the pumps.
3. State point 1, 4, 8 are saturated liquid and state point 10 is saturated vapour.
4. Expansion valves are adiabatic.
5. Pump is isentropic.

The equilibrium temperature and enthalpy of the LiBr-H_2O solution can be obtained by the following equation. The constant coefficient a_i,b_i….e_i can be taken from ASHRAE, Handbook of fundamentals 1997 .

$$T_{sol} = T_{ref}\sum_{i=0}^{3} a_i X^i + \sum_{i=0}^{3} b_i X^i \quad (3.4)$$

$$h_{sol} = \sum_{i=0}^{4} c_i X^i + T_{sol}\sum_{i=0}^{4} d_i X^i + T_{sol}^2 \sum_{i=0}^{4} e_i X^i \quad (3.5)$$

The actual coefficient of performance (COP) is defined as the ratio of cooling effect produced in the evaporator and the heat supplied in the generator.

$$\mathrm{COP} = \frac{\mathrm{Qe}}{\mathrm{Qg}} \quad (3.6)$$

And the overall system efficiency (OSE) of the system can be defined as the ratio of specific cooling effect and the incident radiation [Lazzarin, 2013].

$$OSE = \frac{Q_e}{G} = \frac{Q_e}{Q_g} * \frac{Q_g}{G} = \mathrm{COP} * \eta_c \quad (3.7)$$

In this study the peak cooling load is 31.59 kW, so a 35 kW (10TR) absorption chiller manufactured by YAZAKI is selected. The COP of chiller is taken as 0.7 and auxiliary power consumption of the pump is taken as 210W [Mateous et.al 2009]. The same capacity chiller is used in all the climate because peak cooling load is nearly same except in the moderate climate (Bangalore).The peak cooling load in moderate climate is only 20.83 kW accordingly 7 TR capacity chiller is taken. The value of cooling load is not constant throughout the year as well as the intensity of radiation so a 10.5 kW (3TR) electrical operated chiller with a nominal COP is 3.5 is also used as an additional backup to fulfill the complete demand. The set point temperature for the chillers is taken as 10°C. The other performance data of chiller is taken by default setting of program [TRANSOL].

3.4.5 Cold storage tank

The cold storage tank is installed between the chiller and the cold distribution system. The volume of the cold storage tank is determined based on its two major functions;

1. To meet the daily peak load and
2. To avoid the chiller operation under 20% of the chiller capacity.

The thermal storage capacity Q_s of hot storage tank is given [Hang et al.2010].

$$Q_s = \sum_{i=1}^{n} (L_i - Q_0)\, \Delta t_i \tag{3.8}$$

Here

Q_s is the thermal capacity of the cold storage, kWh;

L_i is the daily cooling load, kW;

Q_0 is the nominal capacity of the chiller, kW;

Δt_i is the time interval of the simulation hr;

n is the total operation periods.

The volume of the cold storage tank is determined by using the equation [Hang et al, 2010]

$$V = \frac{Q_S \times no. of\ hrs. \times 3600}{\rho\, C_p\, \Delta T_{load}} \tag{3.9}$$

Here

V is the volume of the cold storage tank in m^3;

C_p is the specific heat of the water kJ/kg°C;

ρ is the density of water kg/m^3;

ΔT_{load} is the temperature difference of the cold storage tank, °C

In this study the building is used in the day time only so only a 1000 liter cold storage tank is selected having the polyurethane foam insulation of 80 mm thickness to reduce the losses. The heat transfer coefficient is 1.080 kJ/hr-m^2K [TRANSOL].

3.4.6 Cooling tower

The cooling tower is used to reject the heat from the condenser. The fluid used in cooling tower is water. The air volume flow varies between 130-170 m^3/hr per kW of cooling power. The electricity power consumption can be taken as 6-10W per kW of cooling power. In this study a 85 kW capacity cooling tower is selected. Therefore an air flow taken 11000 m^3/hr and fan electricity consumption 0.85 kW are selected [Eicker et al.2014].

3.4.7 Cold distribution system

For cold distribution system a fan coil unit is used. Fan coil unit is a simple device consists of cooling coil and fan. The main parameters used in the cold distribution system are taken as [TRANSOL]

- Cold distribution system - Fan coil
- Forward Temperature-10°C
- Return Temperature-20°C
- Maximum Flow rate- 8600 kg/hr

3.4.8 Control Strategy

Various controls are used here to control the operation of solar thermal cooling system. The following control is employed [Bongs 2009].

Control of the solar loop pump P1

The solar loop is the circuit between the collectors and the heat exchanger. For the control of the solar pump (P1), an irradiation differential controller has been chosen: The primary pump P1 is activated when the radiation is higher than the 300W/m^2 and deactivated when the radiation falls below than 250 W/m^2. The flow rate mode is constant in the collector and taken as 4300 kg/hr (38 l/hr.m^2). The maximum temperature in the primary loop is 102 °C and in the solar tank is 90 °C.

Control of the secondary pump P2

The storage loop is the circuit between the heat exchanger and the hot storage tank. To control the pump P2, a temperature differential controller is used. The pump P2 is switched ON based on two conditions, if the primary pump is ON or the temperature of the collector is more than 4°C of the temperature of the top of the hot storage tank. The flow rate mode is constant in the collector and taken as 4300 kg/hr (38 l/hr.m²).

Control of the hot water loop pump P3

The hot water loop is the circuit between the hot water tank and the chiller. The hot water loop pump switched ON if the temperature of top of hot storage tank is greater than 15°C by the chiller temperature and the temperature of bottom of cold storage tank is greater than 3°C. The hot water loop pump is switched OFF if the temperature of the hot storage tank at top position is less than the temperature of chiller and temperature of bottom of cold storage tank is less than 3°C.The volume flow rate of the pump is taken as the same as primary and secondary pump i.e. 4300kg/hr.

Control of the chilled and cooling water loops (Pump P4, P5)

These pumps are operated in connection to the pump P3. If the pump P3 is ON then the pump P4 and P5 will be ON and similarly will be switched OFF if the pump P3 is switched OFF. The volume flow rate for pump P4 and pump P5 is taken as 18360 kg/hr and 5560 kg/hr respectively.

Control of the pump P6

The pump P6 is used to distribute the chilled water from the cold storage tank to the building. It is switched ON if the temperature of the cold water tank (Bottom position) is less than 12 °C and the demand of building cooling load exists. The volume flow rate is taken as maximum 8600 kg/hr. The table 3.5 shows the pump flow rates and power consumption.

Cooling control

The following parameters are considered to control the chiller operation.

- Thermal chiller set point temperature 10°C
- Generator set point temperature 80°C
- Generator dead band 10°C
- Thermal chiller minimum cooling water temperature 28°C

Table 3.5 Pump flow rates and power consumption [Bongs 2009]

	Pump flow rate	Power consumption (Yazaki)
Pump P1 (Constant flow rate)	4300 Kg/hr	215W
Pump P2 (Constant flow rate)	4300 Kg/hr	215W
Pump P3 (Variable flow rate)	4300 Kg/hr (Maximum)	215W (Maximum)
Pump P4 (Constant flow rate)	18400 Kg/hr	920W
Pump P5 (Constant flow rate)	5500 Kg/hr	270W
Pump P6 (Variable flow rate)	8600 Kg/hr (Maximum)	430W (Maximum)

3.5 Description of Analyzed Solar Photovoltaic Cooling Systems

In the photovoltaic cooling system the energy demand is covered by electricity generated by the PV array and if required the electricity is taken from the public grid. The electricity is also can be fed in the public grid if the generated array power is more than the consumption of energy by the air conditioning devices. The photovoltaic cooling system is modelled in the TRNSYS software. Fig 3.22 shows a schematic of model of PV air conditioner used in TRNSYS simulation program. The power generated by the PV array is regulated and converted into the A.C power by the inverter and supplied to the air conditioner when energy demanded otherwise it is fed to grid. The detail of other component is described in the following section.

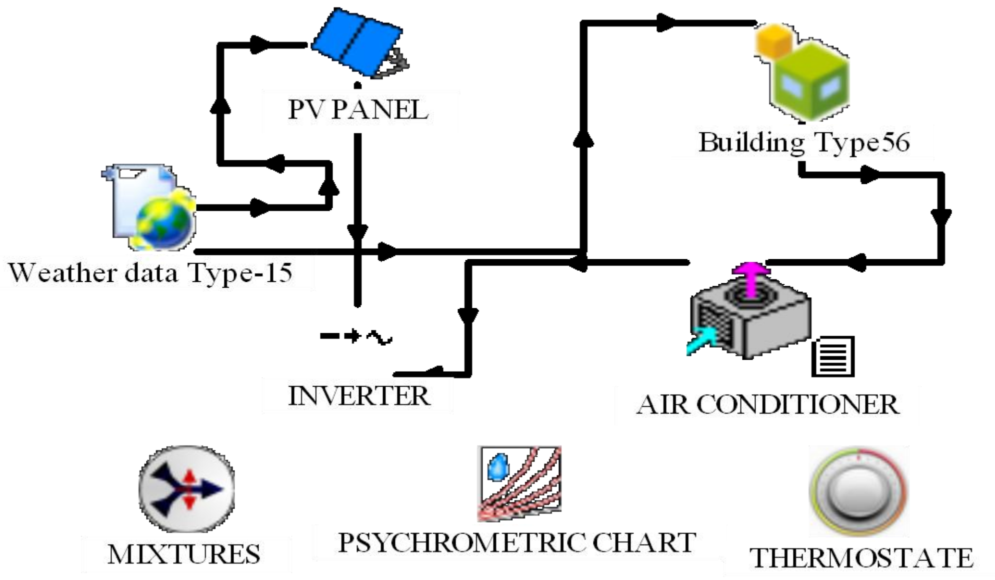


Fig 3.22 Schematic of model used in TRNSYS for PV air conditioner.

3.5.1 Photovoltaic panel

The photovoltaic cells commonly called solar cells, convert sunlight directly into electricity. Solar cells are based on the phenomenon of Photovoltaic effect. The first practical photovoltaic cell was publically demonstrated in 1954 at Bell Telephone Laboratories. In the earliest phase of solar cell development, these solar cells were used for smaller voltage equipments like watches, calculators and space satellites etc. Many solar panels are combined together to create a solar array and when these arrays are interconnected to form a large utility PV system, it can be used for industrial applications or electricity generation. The panels are mounted either at a fixed angle facing south, or can be mounted on a tracking device that follows the sun to capture maximum direct solar radiation. Based on the process of manufacturing and materials used, these solar cells are broadly classified into three types: Mono crystalline, Poly crystalline and Thin film cells.

Mono crystalline

Primary material for the manufacturing of mono crystalline photovoltaic is silicon; in which the crystal lattice of the entire solid is continuous, and free of any grain boundaries. Mono-Si can be prepared intrinsic, containing very small quantities of other elements added to enhance its semi conducting properties. These are manufactured by Czochralski process up to a length of 2 meters and heavily weighted in form of ingots. Once the ingot is formed, it is sliced into a series of thin wafers which are the substrate of the solar cell and have an efficiency of 15-17%. The main problem is due to the process of manufacturing the wafers which is expensive.

Poly crystalline

Similar to mono, polycrystalline cells are also made from silicon crystals of very fine size, but the process differs. Instead of the long, arduous, expensive process of creating a single crystal solar cell (where the ingot is drawn slowly from a vat), the molten silicon is poured into a cast and cooled with a seed crystal (a piece of crystalline material used to grow a larger crystal). Unlike the mono atomic structure, the casting method creates unstructured lattices which results in lowering the overall efficiency of these photovoltaic. Polycrystalline panels are typically 12-14% efficient.

Thin film cells

Thin film cells are the least efficient of the three types, having efficiency in between 6-8%. The panels are made using a CVD process (chemical vapor deposition) in which silicon is deposited typically on glass, plastic or metal. Thin-film solar cells are commercially used in several technologies, including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous and other thin-film silicon (a-Si, TF-Si). Latest generation of thin film photovoltaic use film thickness which varies from a few nanometers (nm) to tens of micrometers (µm), much thinner than thin-film's, first-generation crystalline silicon solar cell (c-Si), that uses silicon wafers of up to 200 µm. This allows thin film cells to be flexible, lower in weight, and have less drag. While this leads to better performance in low light and higher ambient temperatures, it also greatly reduces the cell efficiency.Thin film technology is particularly used in building integrated photovoltaic and as a semi-transparent photovoltaic glazing material that can be laminated on windows.

Type 94 Photovoltaic array

This component models the electrical performance of a photovoltaic array. Type 94 may be used in simulations involving electrical storage batteries, direct load coupling, and utility grid connections. It employs equations for an empirical equivalent circuit model to predict the current voltage characteristics of a single module. This circuit consists of a DC current source, diode, and either one or two resistors. The strength of the current source is dependent on solar radiation and the I-V characteristics of the diode are temperature-dependent. The results for a single module equivalent circuit are extrapolated to predict the performance of a multi-module array. For crystalline modules (either single crystal or polycrystalline technology), Type 94 employs a four-parameter equivalent circuit. The values of these parameters cannot be obtained directly from manufacturers catalogs. However, Type 94 will automatically calculate them from available data. A second equivalent circuit model involving five mathematical parameters is available for amorphous/thinfilm PV modules. Type 94 also includes an optional incidence angle modifier correlation to calculate how the reflectance of the PV module surface varies with the angle of incidence of solar radiation. Type 94 determines PV current as a function of load voltage. Other

OUTPUTS include current and voltage at the maximum power point along the IV curve, open-circuit voltage, and short circuit current[A TRaNsient simulation Program Volume-4, 2009].

Modelling options

A number of simulation options are available for the Type 94 Photovoltaic Array. The first of these is the mathematical model used to predict the electrical performance of the array. The four parameter model should be used to for single crystal or polycrystalline PVs. This assumes that the slope of the I-V curve at short-circuit conditions is zero. The four-parameter model is enabled whenever zero or a positive value is entered for PARAMETER 18. The second PV model, the five-parameter model is intended for amorphous or thin-film PVs. This produces a finite negative slope in the I-V characteristic at the short-circuit condition. When a negative value is entered for PARAMETER 18, Type 94 takes this value to be the short-circuit IV slope and enables the fiveparameter model [A TRaNsient simulation Program Volume-4, 2009].

The second option is whether or not the simulation should call the "incidence angle modifier" correlation. This correlation accounts for the increased reflective losses when radiation is incident on the module at large angles. If PARAMETER 16 is a positive value, TRNSYS will not call the incidence angle modifier. In this case, PARAMETER 16 is the value of the transmittance-absorptance product ($\tau\alpha$) for all angles of incidence. The angle modifier correlation is enabled when a negative value is entered for PARAMETER 16. The magnitude of PARAMETER 16 is then the $\tau\alpha$ product for normal incidence; $\tau\alpha$ for other angles are calculated based on the normal value and an empirical correlation as described in next section.

Finally, the user may choose to enter a value for the module series resistance R_s or to call on Type 94 to calculate R_s from other manufacturers'data. Type 94 reads the series resistance directly from PARAMETER 19 whenever a positive value is given. Zero or a negative value indicates that Type 94 should calculate Rs; the magnitude of

PARAMETER 19 is irrelevant in this case [A TRaNsient simulation Program Volume-4, 2009].

Mathematical Description (Four Parameter)

The four-parameter equivalent circuit model was developed largely by Townsend [1989] and also detailed by Duffie and Beckman [1991]. The model was first incorporated into a TRNSYS by Eckstein [1990], and much of the code in Type 94 comes from Eckstein‘s work. Type 94 employs this model for crystalline PV modules. This model is used whenever TRNSYS PARAMETER 19 (the modules short-circuit IV slope) is set to zero or a positive value. The four parameter model assumes that the slope of the IV curve is zero at the short-circuit condition[A TRaNsient simulation Program Volume-4, 2009].

$$\left(\frac{dI}{dV}\right)_{v=0} = 0 \tag{3.10}$$

This is a reasonable approximation for crystalline modules. The four parameters in the model are $I_{L,ref}$, $I_{o,ref}$, γ, and R_s. These are empirical values that cannot be determined directly through physical measurement. Type 94 calculates these values from manufactures‘catalog data; these calculations are discussed in the following. Fig 3.23 shows the equivalent electrical circuit for four parameter model.

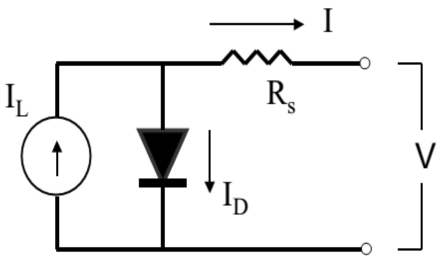


Fig.3.23 : Equivalent electrical circuit four parameter[A TRaNsient simulation Program Volume-4, 2009]

The IV characteristics of a PV change with both insolation and temperature. The PV model employs these environmental conditions along with the four module constants are $I_{L,ref}$, $I_{o,ref}$, γ, and R_s to generate an IV curve at each timestep. The current-voltage equation of circuit shown in fig 3.23 can be written as:[A TRaNsient simulation Program Volume-4, 2009].

$$I = I_L - I_o\left[\exp\left(\frac{q}{\gamma k T_c}(V + IR_s)\right) - 1\right] \tag{3.11}$$

R_s and γ are constants. The photocurrent I_L depends linearly on incident radiation:

$$I_L = I_{L,ref}\frac{G_T}{G_{T,ref}} \tag{3.12}$$

The reference insolation G_{ref} is given as TRNSYS PARAMETER 4. It is nearly always defined as 1000 W/m^2. The diode reverse saturation current I_o is a temperature dependent quantity:

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3 \tag{3.13}$$

Eq .(3.11) gives the current implicity as a function of voltage. Once I_o and I_L are found from Eq. 3.12 and Eq.3.13, Newton's method is employed to calculate the PV current. In addition, an iterative search routine finds the current (I_{mp}) and voltage (V_{mp}) at the point of maximum power along the IV curve.

Calculation of $I_{L,ref}$, $I_{o,ref}$, γ, and R_s

The PARAMETERS for Type 94 include several values which must be read from manufacturers'PV module catalogs. The manufactures' values are used to determine the equivalent circuit characteristics $I_{L,ref}$, $I_{o,ref}$, γ, and R_s These characteristics define an equivalent circuit that is employed to find the PV performance at each timestep[A TRaNsient simulation Program Volume-1, 2009].

Three of these values $I_{L,ref}$, $I_{o,ref}$, γ, may be isolated algebraically. The first step is to substitute the current and voltage into Eq.3.11 at the open-circuit, short circuit, and maximum power conditions:

$$0 = I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{q}{\gamma k T_{c,ref}}V_{oc,ref}\right) - 1\right] - \frac{V_{oc,ref}}{R_{sh}} \tag{3.14}$$

$$I_{sc,ref} = I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{qI_{sc,ref}R_s}{\gamma k T_{c,ref}}\right) - 1\right] - \frac{I_{sc,ref}R_s}{R_{sh}} \tag{3.15}$$

$$I_{mp,ref} = I_{L,ref} - I_{o,ref}\left[\exp\left(\frac{q}{\gamma k T_{c,ref}}\left(V_{mp,ref} + I_{mp,ref}R_s\right)\right) - 1\right] - \frac{V_{mp,ref} + I_{mp,ref}R_s}{R_{sh}} \quad (3.16)$$

In each case the "-1" term is may be dropped to simplify the algebra. This approximation has little influence on the right side of the equations since because the magnitude of I_o is very small, generally on the order of 10^{-6}A. Some rearrangement then yields the following three expressions which isolate $I_{L,ref}$, $I_{o,ref}$, γ :

$$I_{L,ref} \approx I_{sc,ref} \quad (3.17)$$

$$\gamma = \frac{q\left(V_{mp,ref} - V_{oc,ref} + I_{mp,ref}R_s\right)}{kT_{c,ref}\ln\left(1 - \frac{I_{mp,ref}}{I_{sc,ref}}\right)} \quad (3.18)$$

$$I_{o,ref} = \frac{I_{sc,ref}}{\exp\left(\frac{qV_{oc,ref}}{\gamma k T_{c,ref}}\right)} \quad (3.19)$$

At this point an additional equation is needed in order to determine the last unknown parameter. The fourth equation is derived by taking the analytical derivative of voltage with respect to temperature at the reference open-circuit condition. This analytical value is matched to the opencircuit temperature coefficient, a catalog specification:

$$\frac{\partial V_{oc}}{\partial T_c} = \mu_{voc} = \frac{\gamma k}{q}\left[\ln\left(\frac{I_{sc,ref}}{I_{o,ref}}\right) + \frac{T_c \mu_{isc}}{I_{sc,ref}} - \left(3 + \frac{q\varepsilon}{AkT_{c,ref}}\right)\right] \quad (3.20)$$

Where $$A = \frac{\gamma}{N_s}$$

Type 94 uses an iterative search routine in these four equations to calculate the equivalent circuit characteristics. The first step is to set upper and lower bounds for the series resistance parameter R_s: physical constraints require the R_s value to lie between 0 and the value such that $\gamma = N_s$. The initial guess for R_s is midway between these bounds. γ and $I_{o,ref}$ are found from Eq.3.18 and Eq.3.19, while Eq.3.17 gives a trivial solution for $I_{L,ref}$. Type 94 then employs Eq. 3.20 to compare the analytical and catalog values for μ_{voc}. When all other variables are held constant, the analytical value for μ_{voc}

increases monotonically with series resistance. If the analytical voltage coefficient is less than the catalog value, the lower bound for R_s is reset to the present guess value. Likewise, the upper bound is set to the current value if the calculated μ_{voc} is too large. After resetting the upper or lower bound for R_s, a new guess value is found by averaging the bounds. This procedure repeats until R_s and γ converge. Note that for $I_{L,ref}$, $I_{o,ref}$, γ, and R_s are assumed to be constant and are calculated only on the first call in the simulation. Alternatively, the user may enter a known series resistance by entering a positive value for TRNSYS PARAMETER 18. In this case the iterative routine described above is skipped and the 3 equations mentioned here above allow to calculate $I_{L,ref}$, $I_{o,ref}$, γ, and R_s directly from the given value of R_s[A TRaNsient simulation Program Volume-4, 2009].

Mathematical description (5-parameter model)

The four-parameter model described here above does not adequately describe the currentvoltage characteristics of amorphous silicon or thin-film PV modules. There is one major qualitative difference between the I-V curves of crystalline and amorphous PVs. The short-circuit slope of the I-V curve for crystalline modules is very close to zero, while slope for amorphous modules is generally finite and negative. The five parameter model is called whenever TRNSYS PARAMETER 19 (the short-circuit I-V slope) is set to a negative value. This slope is not generally included in the list of module catalog specifications. However, it may be measured if the manufacturer provides a module IV curve at reference conditions. The five-parameter model adds a shunt resistance R_{sh} to the equivalent circuit used in the four parameter model. This circuit is shown in fig 3.24. The four-parameter model may be considered a special case of the five-parameter model in which R_{sh} is infinite. All the equations employed in the five-parameter model reduce to those described for the four-parameter model as the shunt resistance approaches infinity.The current-voltage equation for the equivalent circuit in fig.3.24 is[A TRaNsient simulation Program Volume-4, 2009]:

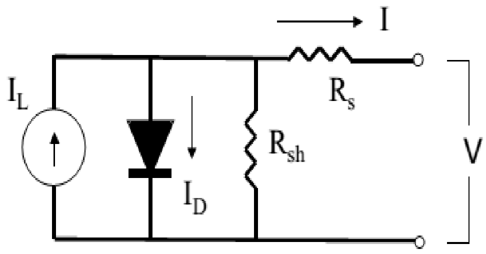


Fig.3.24 : Equivalent electrical circuit five parameter model [A TRaNsient simulation Program Volume-1, 2009]

$$I = I_L - I_o\left[\exp\left(\frac{q}{\gamma k T_c}(V + IR_s)\right) - 1\right] - \frac{V + IR_s}{R_{sh}}$$

(3.21)

As in the four-parameter model, the insolation and temperature dependence of the PV module are given by:

$$I_L = I_{L,ref}\frac{G_T}{G_{T,ref}}$$

(3.22)

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3$$

(3.23)

However, the five-parameter model uses different equations to find the reference values $I_{L,ref}$, $I_{o,ref}$, . The addition of shunt resistance R_{sh} in the circuit element changes the equations used to find the other values $I_{L,ref}$, $I_{o,ref}$, γ, and R_s from available manufacturers' data. Fry [1999] has shown that the negative reciprocal of the short-circuit IV slope closely approximates the shunt resistance:

$$R_{sh} \approx \frac{-1}{\left(\frac{dI}{dV}\right)_{V=0}}$$

(3.24)

This expression reduces the number of unknown quantities to four: $I_{L,ref}$, $I_{o,ref}$, γ, and R_s. Rearranging Eq.3.21 (and neglecting the"-1" at open-circuit, short-circuit, and maximum power conditions yields the following expressions for $I_{L,ref}$, $I_{o,ref}$, γ,

$$I_{L,ref} = I_{sc,ref}\left(1 + \frac{R_s}{R_{sh}}\right)$$

(3.25)

$$I_{o,ref} = \frac{I_{L,ref} - \frac{V_{oc,ref}}{R_{sh}}}{\exp\left(\frac{q}{k\gamma T_{c,ref}} V_{oc,ref}\right)} \tag{3.26}$$

$$\gamma = \frac{\left(q\left(V_{mp,ref} - V_{oc,ref} + I_{mp,ref} R_s\right)\right)}{kT_{c,ref} \ln\left(\frac{I_{L,ref} - I_{mp,ref} - \frac{V_{mp,ref} + I_{mp,ref} R_s}{R_{sh}}}{I_{sc,ref} - \frac{V_{oc,ref}}{R_{sh}}}\right)} \tag{3.27}$$

At this point only R_s is needed to solve the system. An iterative search routine is used to find the correct values for R_s and γ by matching the analytical value for μ_{voc} to that given in the catalog. Differentiating Eq.3.21 with respect to temperature at the open-circuit condition yields

$$\frac{\partial V_{oc}}{\partial T_c} = \mu_{Voc} = \frac{\mu_{Isc} - \frac{I_{o,ref}}{T_c}\left(3 + \frac{q\varepsilon}{AkT}\right)\exp\left(\frac{q}{k\lambda T_{c,ref}}\right)}{\frac{q}{k\lambda T_{c,ref}} I_{o,ref} \exp\left(\frac{q}{k\lambda T_{c,ref}} V_{oc,ref}\right) + \frac{1}{R_{sh}}} \tag{3.28}$$

The search algorithm is similar as for the four-parameter model.

Multi array modules

The electrical calculations discussed for the four-parameter and five-parameter PV models deal only with a single module. Type 94 may be used to simulate arrays with any number of modules. TRNSYS PARAMETERS 10 and 11 define the number of modules in series (NS) and modules in parallel (NP) for the entire array. The total number of modules in the array is the product of NS and NP. When simulating a single module only, both NS and NP are set to 1. The single-module values for all currents and voltages discussed here above are multiplied by NP or NS to find values for the entire array. This approach neglects module mismatch losses [A TRaNsient simulation Program Volume-4, 2009]. The various parameters used here in the simulation are listed in the table 3.6.

Table 3.6 Parameter of photovoltaic panel used for simulation [www.photon.info]

S.No.	Type / Parameters	Mono-crystalline	Poly crystalline	Thin film (CIS)	Unit
1	Make	Bosch Solar Energy AG	C-P Solar CSP250P36	TSMC-Solar TS-125C	
2	Module short circuit current I_{sc}	8.820	7.710	3.33	Ampere
3	Module open circuit voltage V_{oc}	37.90	43.20	58.80	Volt
4	Reference Temperature	298	298	298	K
5	Reference isolation	1000	1000	1000	W/m^2
6	Module voltage at Maxi. Power	30.30	35.30	43.30	Volt
7	Module current at MPPT	8.250	7.090	2.890	Ampere
8	Temperature coefficient Isc	.03%/C	0.065%/C	0.009%C	%/°C
9	Temperature coefficient Voc	-0.127.2mv/C	-186.2mv/C	111.5mv/C	mv/°C
10	Number of cells wired in series	60	72	100	
11	Number of module in series	1	1	1	
12	Number of module in parallel	43-67	40-62	64-101	
13	Module temperature at NOCT	313	313	313	K
14	Ambient temperature at NOCT	293	293	293	K
15	Insolation at NOCT	800	800	800	W/m^2
16	Module area –m^2	1.643	1.752	1.086	m^2
17	Tau-alpha	0.95	-	-	
18	Semi conductor band gap	1.12	-	-	mm
19	Slope of IV curve at Isc	0	-	-	
20	Module series resistance	0.24Ohm	0.336Ohm	2.15Ohm	Ohm

3.5.2 Inverter

In photovoltaic power systems, two power conditioning devices are needed. The first of these is a regulator which distributes DC power from the solar cell array to and from a battery (in systems with energy storage) and to the second component, the inverter. If the battery is fully charged or needs only a taper charge, excess power is either dumped or not collected by turning off parts of the array. The inverter converts the DC power to AC and sends it to the load and/or feeds it back to the utility [A TRaNsient simulation Program Volume-4, 2009].

In photovoltaic systems connected to grid, the key consideration in the design of inverters is to accomplice high efficiency rate with power output for differing power configurations. The inverter connection requires; maximum power point, high efficiency, control power injected into the grid, and low total harmonic distortion of the currents injected into the grid.

Mathematical description

Mode 0 operates without a storage battery component. The power output by the array (P_A) is simply multiplied by effciency1 and sent to the load (as P_L), with any excess fed back to the utility ($P_U < 0$). When the load exceeds the array output, the utility furnishes the difference ($P_U < 0$).

Mode 1 monitors the battery's state of charge, which is input as F. The subroutine performs tests of F against several parameters, the first being with respect to F_C. If $F < F_C$, the battery can either discharge when $P_D > P_A$, or do nothing when $P_D < P_A$. In the latter case, $P_R = P_A - P_L$. If $F < F_C$, the program determines if $F < F_B$ and the battery has been charging ($P_B > 0$). If these two conditions are met, then the battery must be on "total charge." On "total charge," first priority is given to recharging the battery with any array output, rather than sending the output to the load until $F > F_B$. "Total charge" can be avoided by setting $F_B < F_D$; in this case, the first priority for array output is always to meet the load. If $F > F_B$ or the battery has been discharging ($P_B < 0$), it can discharge (when $P_D > P_A$) or be placed on "partial charge" (when $P_D > P_A$), i.e., $P_B + P_A - P_L$. Finally, a check is made to ensure that $F > F_D$. If $F < F_D$ no further discharging is permitted [A TRaNsient simulation Program Volume-4, 2009].

Other conditional statements performed in mode 1 are with respect to the parameter $P_{L,MAX}$, the inverter power output capacity. The solar array and/or battery can never send more than this amount to the load, which means that (P_L)(effciency2) < $P_{L,MAX}$ where $P_{L,MAX}$ is the output power capacity of the inverter, and P_L is multiplied by efficiency 2 upon passing through the inverter.) The $P_{L,MAX}$ limit may require more power to be drawn from the utility, since $P_U = P_D - P_L$ (effciency2) or it may cause excess array output to be dumped into a resistor, with $P_R = P_A - P_L$[A TRaNsient simulation Program Volume-4, 2009].

Mode 2 monitors the battery's voltage level and charge/discharge rate as well as its state of charge. The additional limits are the Inputs V_D, V_C, P_B, $P_{B,MAX}$, and $P_{B,MIN}$. In mode 2, inverter output power is limited to a maximum of $P_{L,MAX}$ if $P_{L,MAX} > 0$. If $P_{L,MAX} < 0$, the current Input to the inverter is limited to a maximum of - $P_{L,MAX}$.

Whenever the "F Tests" call for the mode 2 battery to discharge, the subroutine checks if $V < V_D$. If this is so, then a taper discharge is called for until $F = F_D$. During taper discharge, power is limited so as to never exceed P_{Vd}. If V remains above F_D, then discharge can proceed, as it would in mode 1[A TRaNsient simulation Program Volume-4, 2009].

When state of charge considerations imply charging, a test is performed against V_C. If $V < V_C$, charging can proceed. With $V > V_C$, the battery is put on "slow charge." This means that $P_B = P_C$ where P_C is the power that can be Input to the battery to keep V at V_C . (With the iterative procedure that is performed among the battery, regulator/inverter, and other components, V is effectively limited to exactly V_C .) Thus, the "finishing" charging of the battery is done at constant voltage [A TRaNsient simulation Program Volume-4, 2009].

Modes 0, 1 and 2 all operate with a maximum power mode of the TYPE 50 photovoltaic collector. They simply accept P_A as an Input and parcel it out among P_B, P_R and P_L. Mode 3 involves distributing current instead of power ("P" means "I" in this case), and the solar array voltage is clamped to that of the battery. It takes an initial P_A and sets P_B and the other currents accordingly. Mode 3 performs the same tests as the lower modes on F, V and P_B (now the battery current). It converts the Inputs $P_{L,MAX}$, P_C, P_D, $P_{B,MAX}$ and $P_{B,MIN}$ to currents by dividing by V and the kJ/hr to watt conversion factor 3.6 [A TRaNsient simulation Program Volume-4, 2009].

Modelling options

TYPE 48 models both the regulator and inverter, and can be operated in one of four modes. Modes 0 and 3 are based upon the "no battery/feedback system" and "direct charge system," respectively. Modes 1 and 2 are modifications of the "parallel maximum power tracker system" in the same reference. Here in the simulation simple inverter type 48a is used corresponds to Mode 0: Peak-power tracking collector, no battery, and power is feedback to a utility. In this component the only two inputs are there 1. Input power 2. Load power and it calculates the three outputs 1. Power in 2 Power out 3 Excess power (Power to or from utility (>0 if purchased, <0 if sell-back). The regulator and inverter efficiency is taken as 0.97 [55].

3.5.3 Air conditioner

Vapour compression based air conditioning unit is selected. In TRNSYS simulation program type 921 components represents packaged air conditioning unit for the simulation purpose .This component model an air conditioner for residential or commercial applications. The model requires an external file of performance data that contains the normalized total capacity, sensible capacity and power as a function of the outdoor dry-bulb temperature, the indoor dry-bulb temperature, the indoor wet-bulb temperature, and the normalized evaporator flow rate [A TRaNsient simulation Program Volume-4, 2009]. According to peak cooling demand a 35 kW cooling capacity packaged air conditioning model FVPGR13NY1 is selected for the entire office building in hot and dry, warm and humid, composite climate.The total power consumption of packaged air conditioner is 14.9 kW [Daikin catalogue]. In the moderate climate (Bangalore) the peak cooling capacity is only 20.9 kW accordingly 7TR capacity packaged air conditioner is taken.

Mathematical Description

Type 921 relies on a catalog data lookup method to predict the performance of residential air conditioning devices. The user must provide a single text based data file in the standard TRNSYS data file format. The file must provide normalized values of the air conditioner's total and sensible cooling capacity as well as normalized values of the air conditioner's power draw for varying values of evaporator air flow rates (in liters per second), for varying condenser temperatures (in ºC), for varying indoor air wet bulb temperatures (in ºC) and for varying indoor air dry bulb temperatures (in ºC). Normalized values in the case of Type 921 mean that a value at a particular set of inlet conditions is divided by the corresponding value at the rated inlet condition. A normalized total cooling capacity of 0.8 would mean that the device's current total cooling capacity (given current inlet and ambient conditions) is 0.8 times the device's rated total cooling capacity [A TRaNsient simulation Program mathematical reference Tess model 2014].

Type 921 first performs a call to the TRNSYS psychometrics routine in order to obtain the remaining air properties that are not specified by the user among the component's inputs. If indoor dry bulb temperature and humidity ratio are inputs to the model and a humidity ratio higher than the saturation humidity ratio for that dry bulb temperature is specified, the psychometrics routine will reset the humidity ratio to its saturated condition and print a warning in the TRNSYS list file. Having fully defined the entering indoor air state, Type 921 next determines the volumetric flow rate of evaporator air using the mass flow rate specified by the user and the dry air density returned by the psychometrics routine. It then calls the TRNSYS Dynamic Data routine, which reads the first data file and returns total cooling capacity and total power draw. Type 921 then recalls the Dynamic Data routine to determine the appropriate sensible cooling ratio for the current condition [A TRaNsient simulation Program mathematical reference Tess model 2014].

If the device is ON (based on the current value of the control signal input) then the outlet conditions of the evaporator side air stream are calculated using the following equation [A TRaNsient simulation Program mathematical reference Tess model 2014].

$$T_{evap,out} = T_{evap,in} - \frac{\dot{Q}_{sensible}}{\dot{m}_{evap} Cp_{air}} \qquad (3.29)$$

$$h_{evap,out} = h_{evap,in} - \frac{\dot{Q}_{total}}{\dot{m}_{evap}} \qquad (3.30)$$

$$P_{evap,out} = P_{evap,in} - \Delta P_{evap} \qquad (3.31)$$

The total power draw of the air conditioner, as specified in the data file is assumed to include controller power draw, blower power draw and compressor power draw. Both controller and blower power draw are requested as inputs to the model; the compressor power is simply the difference between the power read from the data file and the combined blower and controller power. The heat rejection of the device (the rate at which heat is rejected from the device to the ambient is calculated using

$$\dot{Q}_{rejected} = \dot{Q}_{total} + Pwr_{total} \qquad (3.32)$$

The COP (coefficient of performance) is:-

$$COP = \frac{\dot{Q}_{total}}{Pwr_{total}} \qquad (3.33)$$

3.5.4 Control strategy

To maintain the desired temperature in the building a simple thermostat type 1503 is selected. For cooling purpose a set point temperature of 24°C is taken with a dead band of 3°C. When the temperature is above the set point it gives a conditional signal to the air conditioning unit and according the air conditioning unit is on and off.

3.6 System Analysis under Different Climatic Conditions

3.6.1 Climatically Classification /Zones in India

Regions having similar characteristic features of climate are grouped under one climatic zone. Based on the climatic factors the country can be divided into a number of climatic zones. According to Bureau of Indian Standards, the country may be divided into five major climatic zones. These zones are designated as hot and dry, warm and humid, composite, moderate (temperate) and cold. The characteristics of the places considered in the present work are taken from the country India. These differences in the weather profile translate unique requirements for building thermal comfort and architectural responses for the different climatic zones. Table 3.7 represents the criteria of this classification as well. Fig.3.25 shows the corresponding climatic classification map of India.

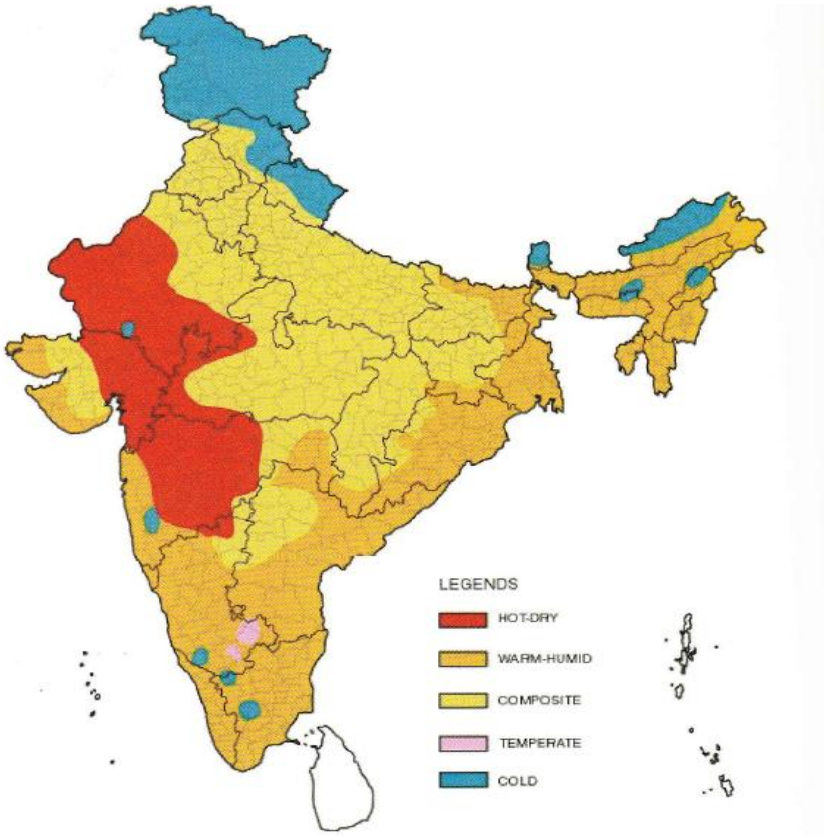


Fig 3.25 Climate Zone Map [ECBC 2009]

Table 3.7 Classification of Climates [National Building Code India 2005]

S.No.	Climate	Mean monthly maximum temperature	Relative humidity (%)
1	Hot and dry	Above 30	Below 55
2	Warm humid	Above 30	Above 55
3	Moderate	Between 25-30	More than 75
4	Cold	Below 25	All values
5	Composite	This applies when the six months or more do not fall within any of the above categories.	

Hot and Dry Climate

Hot and dry climate zone mainly lies between western and central part of India. In a typical hot and dry climate the ambient conditions are very harsh and unfavorable. Due to intense solar radiation (range~800-950 W/m2), the maximum ambient temperature are as high as 40-45° C during daytime and 20-30° C at night; showing a very high diurnal temperature variation in this climatic zone. Relative humidity is generally low for this climate, ranging from 25 to 40% because regions of these climatic zones are usually flat with sandy or rocky ground conditions and low vegetation and surface water bodies. Also rainfall is quite low in this zone having an annual precipitation less than 500 mm. Ahmedabad, Jodhpur and Jaisalmer, are some of the towns that experience this type of climate. In this study Ahmedabad city represents this climate zone, it comes in Gujarat state.

Warm and Humid Climate

Warm and humid climate of India generally covers the coastal parts of country. Due to high relative humidity content in this zone, abundant vegetation is reflected in these regions. Due to cloudy atmosphere, the diffuse fraction of solar radiation is quite high but the radiation is intense on clear days. The ambient temperature is 30-35°C during daytime in summer and 25-30 °C during winter period respectively. Although temperature range is not excessive; the high relative humidity prevailing in these regions causing more discomfort to the occupants. Major cities like Mumbai, Chennai and Kolkata falls under this zone. In this study Chennai city represents this climate zone, it comes in Tamilnadu state.

Moderate Climate

Areas of these climatic zones are generally located on hilly or high plateau regions of country with fairly abundant vegetation. Since solar radiation in this region is more or less the same throughout the year; reflecting the temperatures are neither high nor low.In summers, the temperature reaches 30 – 34 ºC during the day while in winter, the maximum temperature is between 27– 33 ºC during the day having a relative humidity of range 20-55 %, and high up to 90% during monsoons.The total rainfall usually exceeds 1000 mm per year. Bangalore and Pune are examples of cities that fall under this climatic zone. In this study Bangalore city represents this climate zone, it comes in Karnataka state.

Cold and Cloudy Climate

Generally, the Himalayan region and northern part of country covers this type of climate. Cities like Srinagar, Shimla, and Shillong, are examples of places belonging to this climatic zone. Due to low intensity of solar radiation in these regions (only diffuse radiations), winter season are extremely cold. However in summer, the diurnal temperature range lies between 20-30°C during the day and 17-27°C at night making summer more comfortable and pleasant. The relative humidity is generally high and ranges from 70 – 80 %. Annual total precipitation is about 1000 mm and is distributed evenly throughout the year. In this climate the requirement of cooling is very low hence this climate is not considered for in the present study.

Composite climate

Central part of India having variable landscape and seasonal vegetation are covered in this climatic zone. A very high intensity solar radiation with diffuse radiation in summer season increases ambient temperature up to the range of 32-43°C in daytime and nighttime values are from 27 to 32° C. In winter, the values are 10 to 25 ºC during the day and 4 to 10 ºC at night.The relative humidity is about 20 – 25 % in dry periods and 55 – 95 % in wet periods. Precipitation in this zone varies between 500 – 1300 mm per year. Delhi, Kanpur, Allahabad etc are comes in this climates. In this study Delhi city represents the composite climate. Table 3.8 shows the classifications of different climates zone in India and their main features.

Table 3.8 Classifications of different climates zones in India [ECBC 2009]

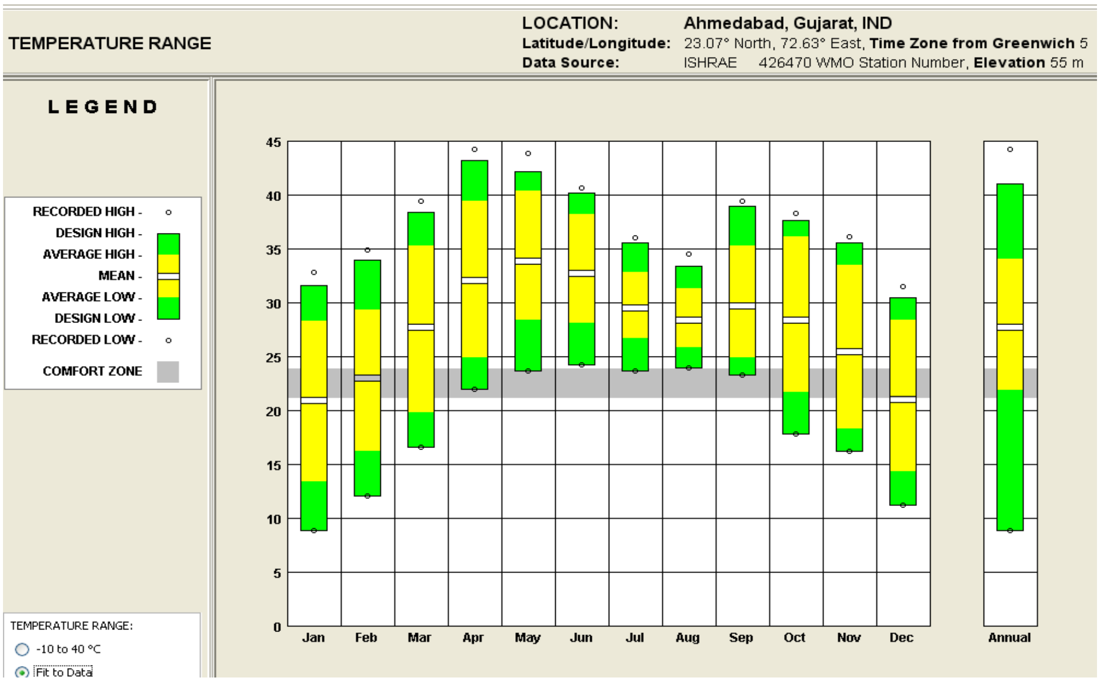
		Summer midday (High)	Summer night (Low)	Winter midday (High)	Winter night (Low)	Diurnal Variation				
Hot and Dry	High temperature | Low humidity and rainfall | Intense solar radiation and a generally clear sky | Hot winds during the day and cool winds at night | Sandy or rocky ground with little vegetation |Low underground water table and few sources of surface water.	40 to 45	20 to 30	5 to 25	0 to 10	15 to 20	Very Low 25-40%	Low <500 mm/yr.	Cloudless skies with high solar radiation, causing glare	Rajasthan, Gujarat, Western Madhya Pradesh,Central Maharashtra etc.
Warm and Humid	Temperature is moderately high during day and night | Very high humidity and rainfall | Diffused solar radiation if cloud cover is high and intense if sky is clear | Calm to very high winds from prevailing wind directions | Abundant vegetation | Provision for drainage of water is required	30 to 35	25 to 30	25 to 30	20 to 25	5 to 8	High 70 to 90%	High > 1200 mm/yr.	Overcast (cloud cover ranging between 40 and 80%), causing unpleasant glare	Kerela, Tamilnadu, Costal parts of Orissa and Andhra Pradesh etc.
Temperate	Moderate temperature | Moderate humidity and rainfall | Solar radiation same throughout the year and sky is generally clear | High winds during summer depending on topography | Hilly or high plateau region with abundant vegetation	30 to 34	17 to 24	27 to 33	16 to 18	8 to 13	High 60 to 85%	High > 1000 mm/yr	Mainly clear, occasionally overcast with dense low clouds in summer	Bangalore, Goa and parts of the Deccan
Cold (Sunny/ Cloudy)	Moderate summer temperatures and very low in winter | Low humidity in cold/sunny and high humidity in cold/cloudy | Low precipitation in cold/sunny and high in cold/cloudy | High solar radiation in cold/sunny and low in cold/cloudy | Cold winds in winter | Very little vegetation in cold/sunny and abundant vegetation in cold/cloudy	17 to 24/20 to 30	4 to 11/17 to 21	(-7) to 8 /4 to 8	(-14) to 0 /(-3) to 4	25 to 25 /5 to 15	Low: 10-50% /High: 70-80%	Low: < 200 mm/yr /Moderate 1000mm/yr	Clear with cloud cover < 50% / Overcast for most of the year	Jammu &Kashmir, Ladakh, Himachal Pradesh, Uttaranchal, Sikkim, Arunachal Pradesh
Composite	This applies when 6 months or more do not fall within any of the above categories | High temperature in summer and cold in winter | Low humidity in summer and high in monsoons | High direct solar radiation in all seasons except monsoons high diffused radiation | Occasional hazy sky Hot winds in summer, cold winds in winter and strong wind in monsoons | Variable landscape and seasonal vegetation	32 to 43	27 to 32	10 to 25	4 to 10	35 to 22	Variable Dry Periods= 20-50% Wet Periods= 50-95%	Variable 500-1300 mm/yr, during monsoon reaching 250 mm in the wettest month	Variable Overcast and dull in the monsoon	Uttar Pradesh, Haryana, Punjab, Bihar, Jharkhand, Chattisgarh, Madhya Pradesh etc.

3.6.2 Weather Data Analysis

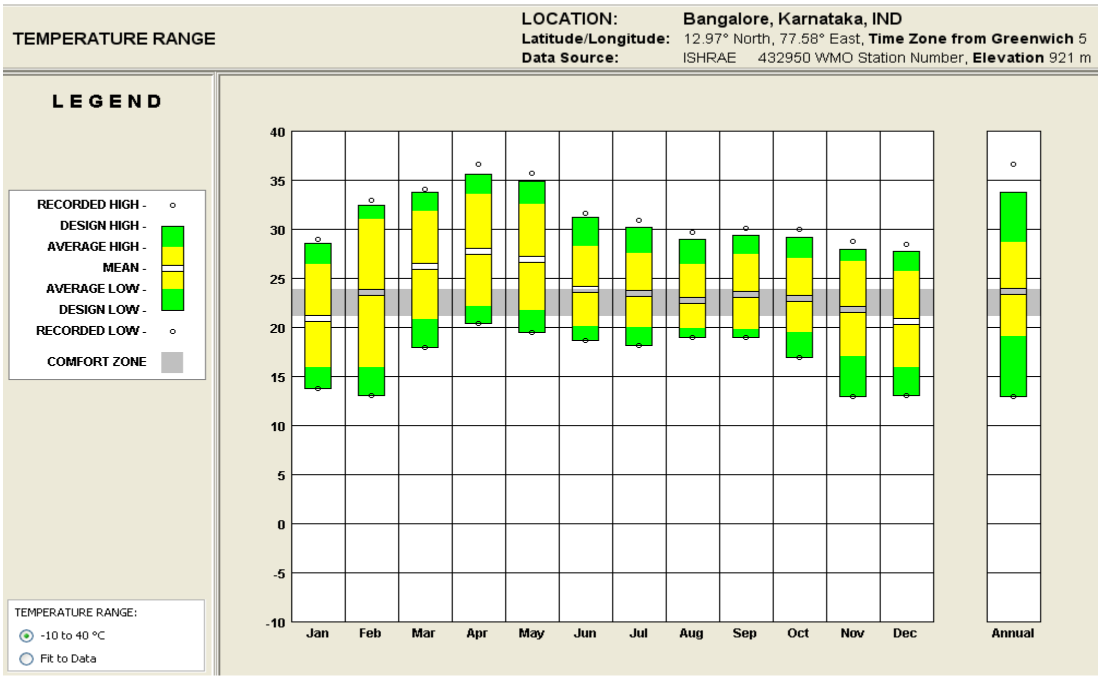
In this study four major cities with different climatic zones are simulated. Ahmedabad, Bangalore, Chennai and Delhi represent hot and dry, moderate, warm and humid and composite climate, respectively.

Temperature

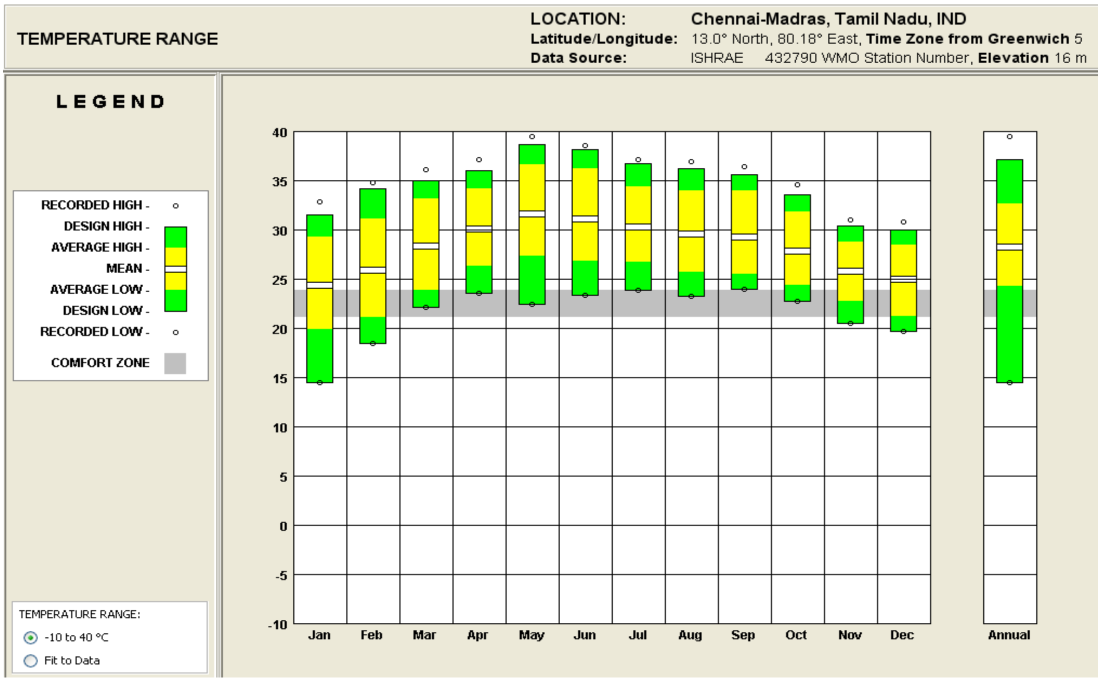
Figures 3.26 (a), (b), (c) and (d) show the monthly variation of temperature (high, mean, average) for the Ahmedabad (Hot and dry), Bangalore (Moderate), Chennai(Warm and humid) and Delhi (Composite) respectively. It is clear from the fig 3.26 (b) that in the moderate climate the variation in the temperature is very low, while in the hot, dry and composite climate the variation in the temperature is very high during the whole year. For hot and dry climate, the maximum temperature is 44.20°C, in the moderate climate 36.60°C, in the warm and humid climate 39.50°C and in the composite climate 44.30°C. The minimum temperatures are in the composite climate represented by Delhi as low as 5°C in the months of January and December while in the other climate it is higher than 5°C. It has been observed for city Ahmedabad the mean temperature is above the comfort zone from March to November, for city Bangalore the mean temperature is above the comfort zone from March to June, for city Chennai the mean temperature is above the comfort zone almost throughout the year and for city Delhi the mean temperature is above the comfort zone from April to October. The cities have the longer period, for that the mean temperature is above the comfort zone temperature has the higher cooling energy demand.


TEMPERATURE RANGE
LOCATION: Ahmedabad, Gujarat, IND
Latitude/Longitude: 23.07° North, 72.63° East, Time Zone from Greenwich 5
Data Source: ISHRAE 426470 WMO Station Number, Elevation 55 m
LEGEND
RECORDED HIGH -
DESIGN HIGH -
AVERAGE HIGH -
MEAN -
AVERAGE LOW -
DESIGN LOW -
RECORDED LOW -
COMFORT ZONE
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Annual

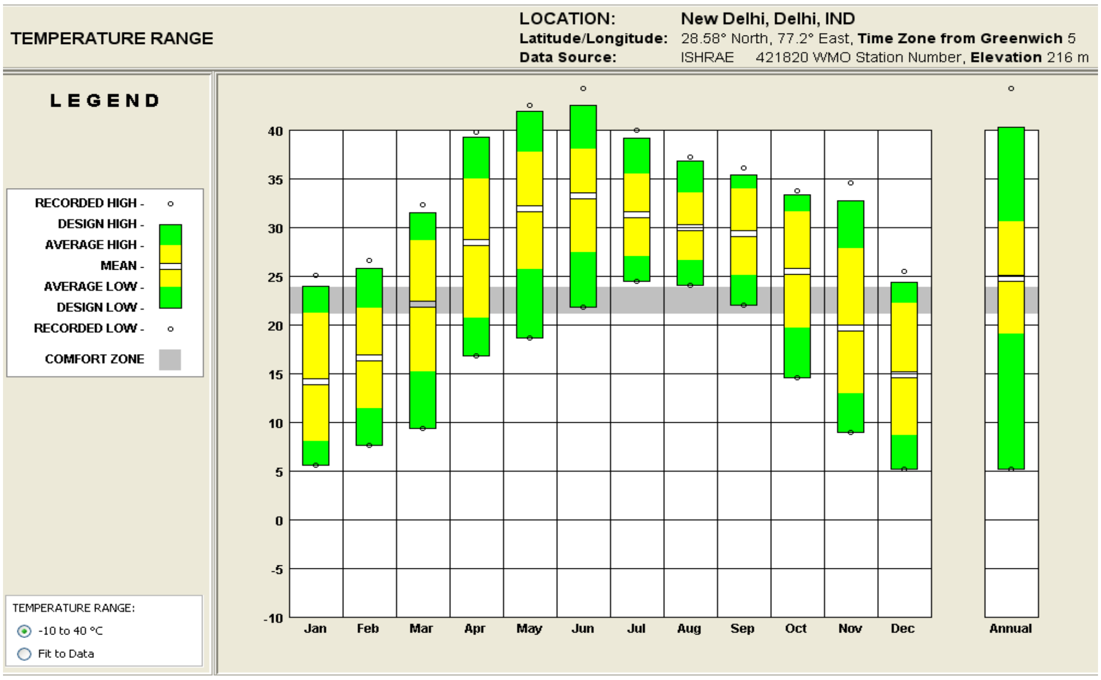
(a)


TEMPERATURE RANGE
LOCATION: Bangalore, Karnataka, IND
Latitude/Longitude: 12.97° North, 77.58° East, Time Zone from Greenwich 5
Data Source: ISHRAE 432950 WMO Station Number, Elevation 921 m
LEGEND
RECORDED HIGH -
DESIGN HIGH -
AVERAGE HIGH -
MEAN -
AVERAGE LOW -
DESIGN LOW -
RECORDED LOW -
COMFORT ZONE
TEMPERATURE RANGE:
-10 to 40 °C
Fit to Data
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Annual

(b)



(c)



(d)

Fig. 3.26 Monthly variation of temperature (a) Ahmedabad, (b) Bangalore, (c) Chennai and (d) Delhi

Relative humidity

Fig. 3.27 shows the monthly average variation of relative humidity for the simulated cities for respective climatic zones. It is clear from the fig.3.27 that the relative humidity is very high in Chennai because it has warm and humid climate, whereas in Delhi the relative humidity is very low in the months of April and May because warm winds blow during that period. The value of relative humidity is very high from July to September due to rainy season almost for all climatic zones and low in the summer season from March to May.

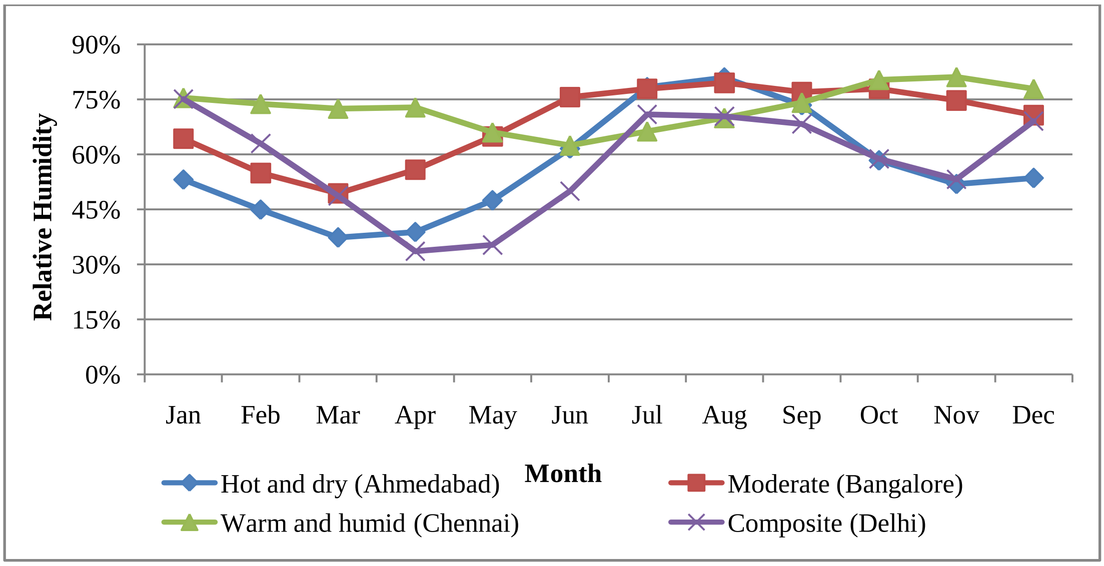


Fig. 3.27 Monthly average variation of relative humidity

Daily solar radiation

Fig. 3.28 shows the monthly average variation of daily solar radiation for the representative cities in each climatic zones and it has been observed that the global horizontal radiation is high in the months of March, April and May in typical summer season and low in the months from October to January typical winter season. The global horizontal radiation is highest for the Ahmedabad (hot and dry) and lowest for Chennai (Warm and humid). In the Delhi the radiation is highest in the month of March to July. In December to February the lowest radiation is in the Delhi (Composite). Table 3.9 shows the climatic condition of different representative cities.

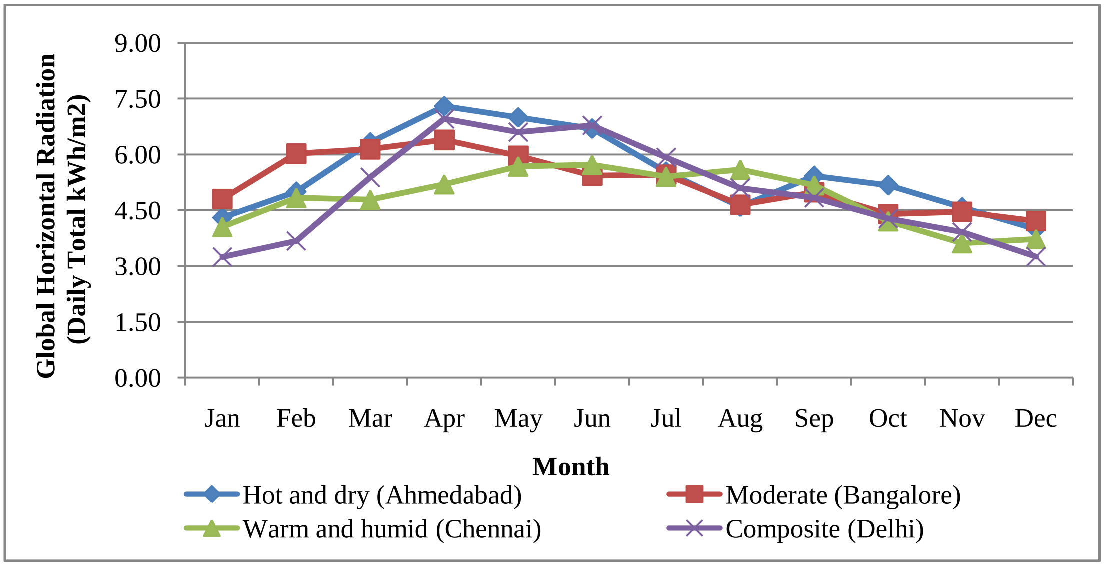


Fig. 3.28 Monthly average variation of global horizontal radiation

Table 3.9 Climatic condition of different representative cities

S.No.	**City / Parameters**	**Ahmedabad**	**Bangalore**	**Chennai**	**Delhi**
1	Climate Zone	Hot and Dry	Moderate	Warm and Humid	Composite
2	Latitude ˚N	23.07	13.0	13.0	28.6
3	Longitude ˚E	72.6	77.6	80.2	77.1
4	Elevation (m)	55	921	16	233
5	Maximum Temp.(C)	44.20	36.60	39.50	44.30
6	Average RH (%)	56.7	68.6	72.7	58.1

3.7 Energy Performance Analysis

The various cases of solar thermal and solar photovoltaic cooling systems are simulated using the different parameters like types of collector, collector area and climate conditions. In these simulations some parameters come as the primary output result and some are derived from that. The details are as the energy performance evaluated with the following parameters.

3.7.1 Annual total electricity consumption

The annual total electricity consumption of the system is calculated by summing the energy consumed by the recirculation pump, distribution pumps, controls (including when the system is in standby) and the thermal chiller and cooling tower . It also includes the energy consumed by the compressor and the fan of the condenser in the case of electric chiller used as the backup. These values are given by the program TRANSOL. In the case of photovoltaic cooling system the energy demand is covered by the photovoltaic modules and if required energy is taken from the public grid. In this way if the electricity demand is higher than the electricity provided by the photovoltaic modules this difference is considered for the calculation of the total power consumption from the grid. If the electricity produced by the photovoltaic panel is higher than demanded by air conditioning system the surplus electricity if fed to public grid and termed as excess power. The value of energy consumption by air conditioning system, grid power consumption, photovoltaic power generation and excess power are given by the program TRNSYS.

3.7.2 Annual useful solar heat

The annual useful solar heat is equal to the heat required for the absorption cooling machine Q_3, and the available solar energy for the heating (Q_{12}) and domestic hot water (Q_{14}). In this study only cooling mode is considered. The other variables used for the calculation parameters are necessary for the energy evaluation of the thermal solar cooling systems which are the annual radiation on the collector (Q_1), annual heat produced by the solar collector (Q_2), annual overall cold production by the absorption cooling machine (Q_6) and the annual cold production by the compression machine(Q_7). These values are given by the TRANSOL simulation.

3.7.3 Annual net collector efficiency

It is defined as the ratio of annual useful heat and annual heat on collector plane (Q_1).

$$Annual\ net\ collector\ efficiency = \frac{Annual\ useful\ heat\ (kWh)}{Annual\ radiation\ on\ collector\ plane(kWh)} \times 100\%$$

$$= \frac{Q_3}{Q_1} \times 100\% \tag{3.34}$$

3.7.4 Specific useful net collector output

It is the ratio of annual useful heat and the collector area.

$$Specific\ useful\ net\ collector\ output = \frac{Annual\ useful\ solar\ heat\ (kWh)}{Collector\ area\ (absorber\ )m^2}$$

$$= \frac{\mathrm{Q}_3 + \mathrm{Q}_{12} + \mathrm{Q}_{14}}{\text{Collector area (absorber)}} \qquad (3.35)$$

3.7.5 Solar fraction

It is the ratio of the cooling produced by the solar and total annual cooling demand of the building.

$$Solar\ fraction\ = \frac{\text{Cooling produced by solar absorption}}{\text{Annual coling demand}}$$

$$= \frac{Q_7}{Annual\ coling\ demand} \qquad (3.36)$$

3.7.6 Electrical (Grid) COP

The electric (Grid) COP of the thermal solar system is calculated considering the annual cooling demand of the building divided by the annual consumption of energy for all the systems considering the energy consumed by the electrical chiller used as a back-up. The electric COP of the photovoltaic cooling system is calculated as the total annual cooling demand of building divided by the power consumed from the grid.

3.7.7 Annual primary energy consumption

The Primary energy is stored in the nature. Common primary energy sources are coal, oil, natural gas, and biomass (such as wood). Other sources available include nuclear energy, thermal energy stored in earth's interior, and potential energy due to earth's gravity. Primary energy sources are mostly converted in industrial utilities into secondary energy sources; for example coal, oil or gas converted into steam and electricity and even these sources may also be utilized directly. The annual primary energy consumption is calculated from the annual total electricity consumption divided by the factor used for conversion of primary energy into electricity.

$$Annual\ primary\ energy\ consumption = \frac{\text{Annual total electricty consumption}}{\text{Primary energy conversion factor}} \qquad (3.37)$$

3.7.8 Relative primary energy savings

The relative primary energy saving is defined as the percentage saving of primary energy by use of solar system with reference to the primary energy consumption by reference system that uses electricity from grid. The relative primary energy saving calculated by the following formula.

$$\text{Primary energy savings} = \frac{\text{Annual primary energy consumption(reference)} - \text{Annual primary energy consumption (solar)}}{\text{Annual primary energy consumption(reference)}} \quad (3.38)$$

3.8 Financial Evaluation Criteria

Investment costs for the installation of solar thermal and photovoltaic cooling systems are much higher than those of conventional vapour compression air conditioner operated by grid power. So a financial analysis is necessary to compare these systems.

3.8.1 Capital cost

The first time investments on equipment, component and machinery are in the category of capital cost. In the solar thermal cooling system it is the sum of cost of solar collector, hot storage tank, vapour absorption machine, cold storage tank, cooling tower, and pumps. In the case of solar photovoltaic cooling system it is sum of cost of photovoltaic panel, civil and general works, mounting structures, power conditioning units and air conditioning units.

3.8.2 Annual operation and maintenance cost

This cost is associated with the maintenance cost of the machinery including the solar and non solar component and operation cost is the cost of energy consumption per year.

3.8.3 Cost of saved primary energy

It is the ratio of annual extra cost of the solar system and the annual primary energy savings by the system.

$$Cost\ of\ saved\ primary\ energy = \frac{\text{Annual extra cost of solar system}}{\text{Annual primary energy savings}} \quad (3.39)$$

3.8.4 Payback period:

Payback time for each option is calculated using the following equation [Eicker et al.2014].

$$\text{Pay back time} = \frac{\text{Final total investment cost (solar system)} - \text{Final total investment cost (reference)}}{\text{annual operation and maintainance cost(reference system)} - \text{annual operation and maintainance cost (solar system)}} \quad (3.40)$$

3.8.5 Internal rate of return (IRR)

It is widely accepted discounted measure of investment worth and is used as an index of profitability for the project. The IRR is defined as the rate of interest that equates the present value of a series of cash flows to zero. In other words it is the interest rate at which the NPV of an investment is zero. Mathematically, the internal rate of return is the interest rate i* that satisfies the following equation [Chandel et al.2013].

$$NPV(i^*) = \sum_{i=0}^{n} \frac{B_n - C_n}{(1 + i^*)^j} = 0 \quad (3.41)$$

Here B_n = benefits associated with the nth year; C_n = cost associated with the n_{th} year

3.9 Assumptions

Although in this work most of the component size, parameters, cost etc. are taken from as per the designed, available literature and market, still some assumption are taken that are listed here.

1. The solar thermal cooling system is modelled in TRANSOL program (A product of TRANSYS) while the solar photovoltaic cooling system is modelled in TRNSYS. For modelling of solar thermal cooling system in TRNSYS, sufficient data was not available for validation. In the literature sufficient data suitable for validation of solar thermal cooling system based on TRANSOL program was available.
2. The specifications of collectors used in this study are taken from the library of the TRANSOL program and those collector models are used which are validated by the Canadian Software Testing Board (CSTB) because the Program TRANSOL is also developed by CSTB.

3. The size of absorption chiller/compression machine is taken equal 35 kW (10TR) in three climates namely hot and dry, warm and humid, composite because the peak cooling load are nearly same i.e. 31.1 kW, 28.3 kW and 31.6 kW respectively. Oversizing of absorption/compression stsyem is taken to compensate the piping and ducting losses. For moderate climate the peak cooling load is 20.9 kW so the size of absorption chiller/compression system is taken as 24.5 kW (7TR). The cost of the 24.5 kW systems is assumed proportionally to 35 kW systems.
4. The capacity of hot and cold storage tank is kept constant on the basis of findings of Hang et al. 2011 in which up to 2% and 6% increase in solar fraction was reported upon increase in the capacity from 4 m^3 to 22 m^3 for cold storage and 2 to 22 m^3 for hot storage tank.
5. The cooling system which offers solar fraction less than 0.50 are not technically feasible. However, they may be financially feasible.

CHAPTER 4 PERFORMANCE ANALYSIS OF SOLAR THERMAL COOLING SYSTEM

In this chapter the modeling results and performance analysis of solar thermal cooling system described in chapter 3 sub sections 3.4 are presented and discussed.

4.1 Modeling of Solar Thermal Cooling System

The solar thermal cooling system consists of solar collectors, hot storage tank, vapour absorption chiller, cold storage tank, cooling tower and cold distribution system. The capacity of vapour absorption chiller is based on the peak cooling load of the building. In this study the cooling load of 225 m^2 square building was calculated by the TRNSYS simulation program and the peak cooling load is 31.2 kW for the composite climate (Delhi). The peak cooling load of hot and dry, warm and humid, composite climate are nearly same so a 35 kW capacity vapour absorption chiller (VAC) is selected which have the COP 0.7 and pump power consumption of 210W. A cooling tower of 85 kW capacity is selected because the generator capacity of VAC is 50 kW and heat rejection in the condenser is 85 kW. In the moderate climate the peak cooling load is only 20.83 kW so 24.5 kW (7TR) capacity vapour absorption chiller is selected. The capacity of absorption chiller is taken slightly higher due to piping and ducting losses.

A hot storage tank of 5000 liter and a cold storage tank of 1000 liter are used for the steadily operation [Eicker et al. 2014]. According to Henning et al.2007 the collector area varied between 1.26 and 4.29 m^2 per kW of cooling capacity for various types of solar thermal cooling systems. For absorption cooling system it is 2.77m^2/ kW cooling capacity so here 90 m^2 collector areas was used. However the collector area is not defined in similar ways for all the system it is different for particular applications and depending on climatic conditions. So in this study the wide variance of collector area 70-110 m^2 are taken with an interval of 10 m^2. The other parameters related to pump are already defined in the chapter 3.

4.2 Model Validation of Solar Thermal Cooling System

After the maximum cooling load of the building was calculated the model of solar thermal cooling system was made in the TRANSOL software using the component SCH601 and selecting the appropriate input data and parameters. Before carrying out the detailed simulation of the system the model should be calibrated and validated either by the previous publication or experiential work. In this research the model was validated by the work of Eicker et al. (2014). They carried out the simulation of solar thermal cooling system for three different climates using four types of buildings so a total of 12 cases are simulated. Table 4.1 shows the climate data for the Palermo (Italy), Madrid (Spain) and Stuttgart (Germany) city. Table 4.2 shows the cases considered for the simulation along with the properties of construction according to the available options of the program TRANSOL and representative U-values for different wall types and windows corresponding to Palermo, Madrid and Stuttgart.

Table 4.1 Climatic conditions in Palermo, Madrid and Stuttgart [Eicker 2014]

City	Coordinates	Climates	Maxi.Temp(°C)	Mini. Temp (°C)	Altitude(m)
Palermo	38.07N, 13.22E	Mediterranean	28.8	8.2	14
Madrid	40.23 N, 3.43E	Mediterranean	31.2	2.6	667
Stuttgart	48.46N, 9.10E	Oceanic	20	0	245

Table 4.2 Cases Considered for the Simulation

Case	City	Building Type	U-Value (W/m^2K)	Type of Window	Sun Protection	Internal Load	Solar Collector Inclination (Degree)	Annual Cooling Demand (kWh_{th}/m^2)
1	Palermo	1	1.10	Single clear	Yes	Low	35	45.79
2	Palermo	4	0.41	Triple clear	Yes	Low	35	61.15
3	Palermo	1	1.10	Single clear	No	High	35	94.24
4	Palermo	4	0.41	Triple clear	No	High	35	140.99
5	Madrid	2	0.66	Double clear	Yes	Low	40	33.93
6	Madrid	4	0.41	Triple clear	Yes	Low	40	35.64
7	Madrid	2	0.66	Double clear	No	High	40	88.34
8	Madrid	4	0.41	Triple clear	No	High	40	96.52
9	Stuttgart	3	1.10	Double clear	Yes	Low	45	8.4
10	Stuttgart	4	0.41	Triple clear	Yes	Low	45	16.76
11	Stuttgart	3	1.10	Double clear	No	High	45	31.28
12	Stuttgart	4	0.41	Triple clear	No	High	45	54.11

4.2.1 Annual cooling load of building

Fig. 4.1 shows the annual cooling demand of various simulated cases and it has been observed that the annual cooling demand is high for Palermo city in comparison to Madrid and Stuttgart city because of the high ambient temperature. Cases without sun protection (3, 4, 7, 8, 11 and 12) have high cooling demand in comparison to the cases with sun protection (1, 2, 5, 6, 9 and 10). The simulated cases in Stuttgart city (9-12) have low cooling demand due to shorter cooling period in a year. The annual cooling demand coming out from simulation for this study has good matching with the annual cooling demand of Eicker et al. (2014). The cooling load has better matching for the Palermo and Madrid city in comparison to Stuttgart city because it has shorter cooling period due to the low ambient temperature. The good agreement in the cooling demand has a validation for the building load.

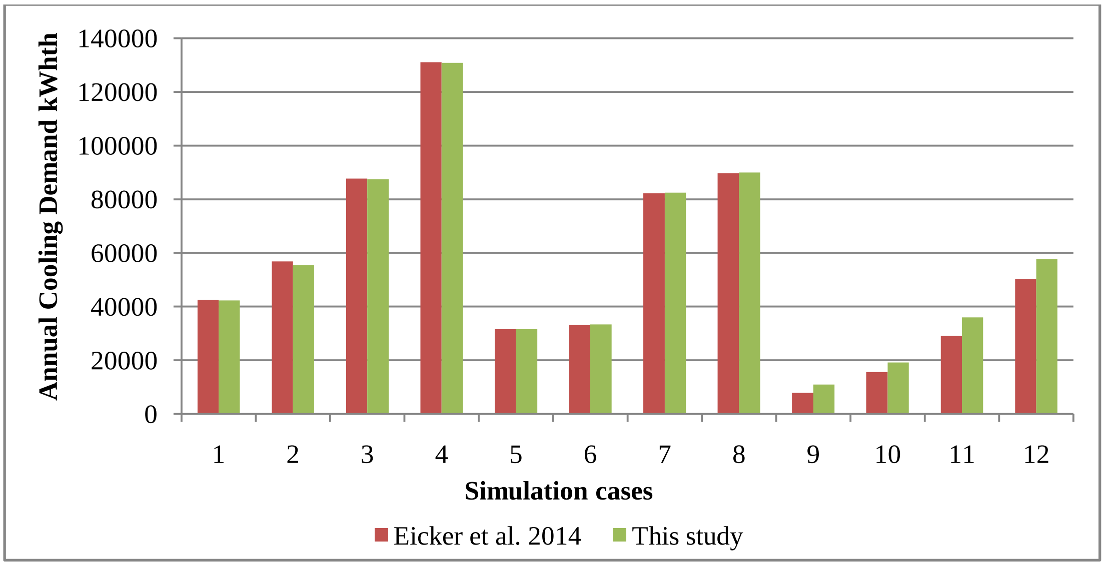


Fig. 4.1 Annual cooling demand for the simulated cases

4.2.2 Annual heat produced by solar collector

Fig. 4.2 shows the annual heat produced by the solar collector for different simulated cases. The heat production in the cases of sun protection is lower than the cases without sun protection for all types of buildings. As a result in the cases of sun protection the cooling load is lower than the cases without sun protection so the demand of the heat is low. The annual heat produced in the building type 4 is more than the building type 1, 2 and 3 because the cooling load is high for type 4 building having lower U-value. As the cooling load is high for the particular building the demand of heat required for the absorption system is high and production of solar heat is as high as possible for the type of collector used here. It has been observed that in the cases without sun protection the simulation result of this study is matching better than with sun protection because of the high cooling load in that cases. The same trend is observed in all types of climates.

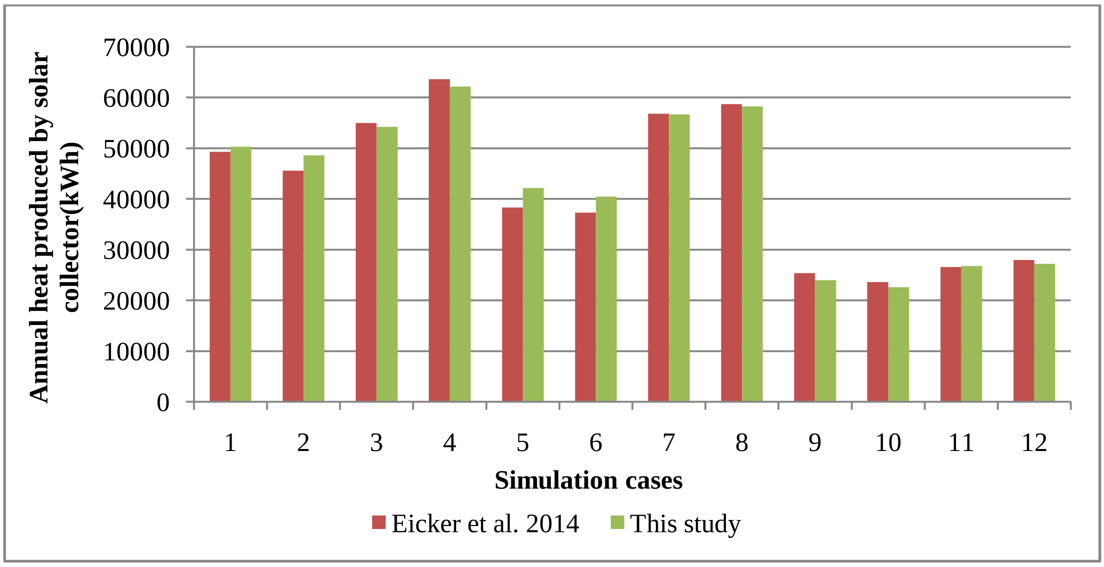


Fig. 4.2 Annual heat produced by solar collector for simulated cases

4.2.3 Annual net collector efficiency

Fig. 4.3 shows the net collector efficiency for the simulated cases and it is clear that there is good matching between this study and Eicker et al. (2014). The results are better matched for the building type 3 and 4 having the high cooling demand in all climatic zones because high cooling demand requires high heat for the generator of the absorption system and utilizes full collector heat resulting in better efficiency.

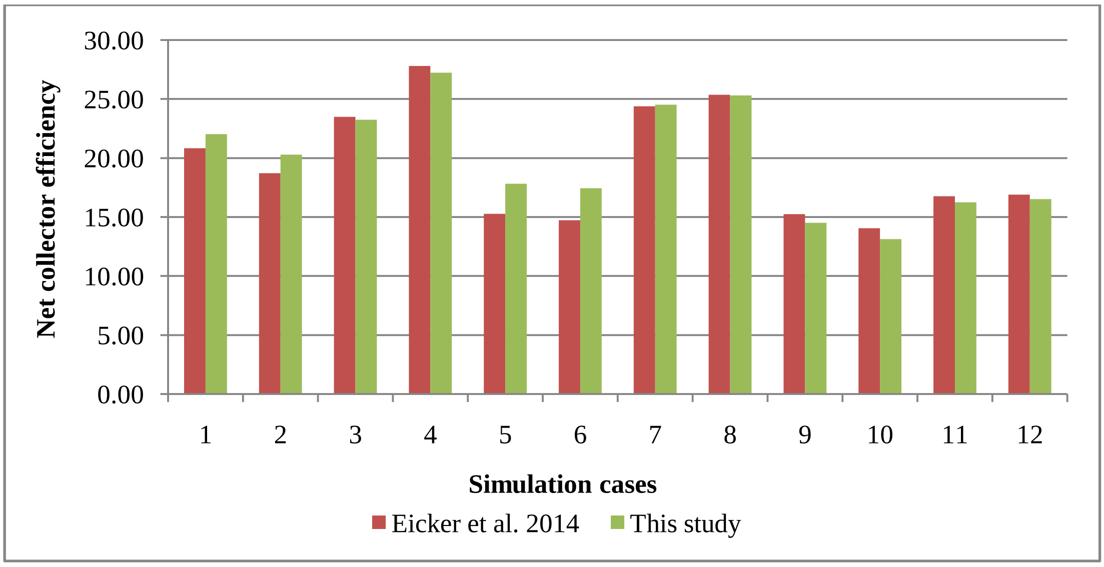


Fig 4.3 Net collector efficiency

4.2.4 Annual absorption and compression cooling

Figures 4.4 and 4.5 show the annual absorption and compression cooling for the various simulated cases. It has been observed that the results have a good agreement with Eicker et al. (2014). It had also been observed that in cases (3, 4, 7, 8, 11 and 12) having high cooling demand the annual absorption cooling is less comparable to the other cases considered for simulation. The remaining annual cooling is fulfilled by the electric compression based cooling system. If the cooling produced by the absorption system is low for a particular case then the electric compression cooling will be more.

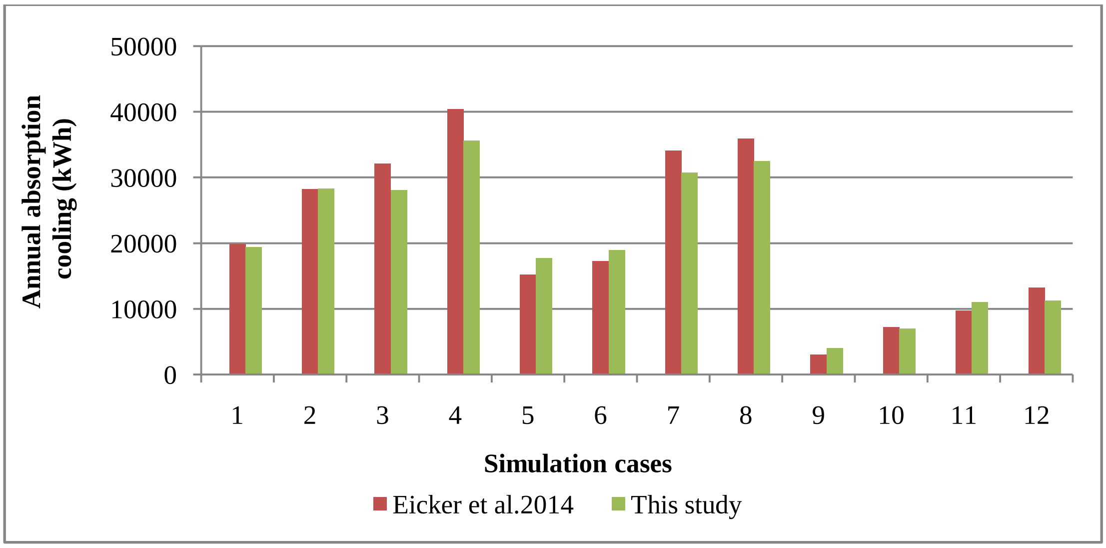


Fig. 4.4 Annual absorption cooling

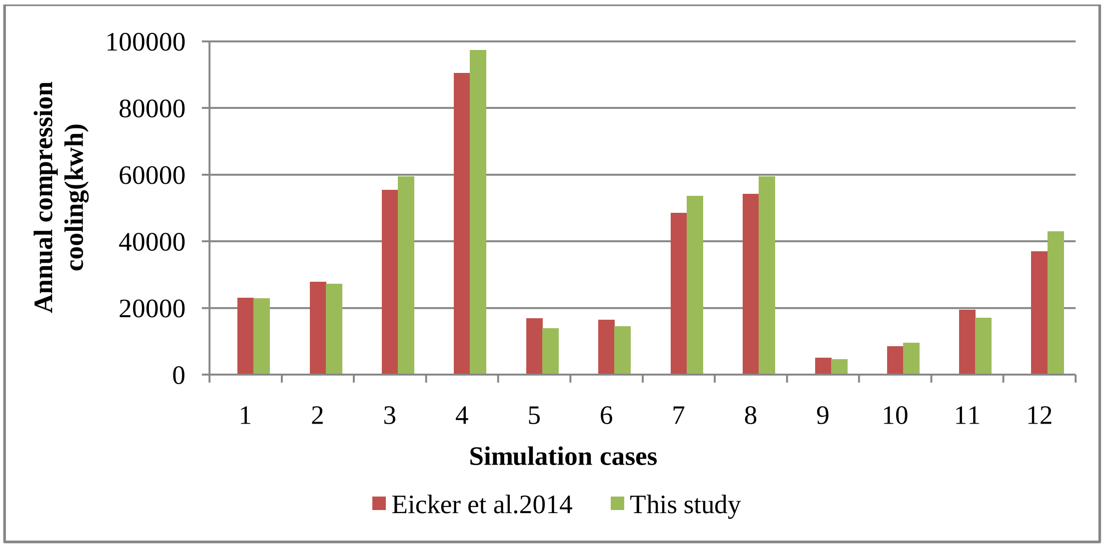


Fig. 4.5 Annual compression cooling

4.2.5 Specific useful net collector output

Specific useful net collector output is the ratio of annual useful heat produced by the collector and the collector area. Fig. 4.6 shows the specific useful net collector output for the considered simulated cases and it is clear from the fig.4.6 that specific useful net collector output is high for Palermo city because of the high solar radiation and high cooling load of the building. It is least for Stuttgart city due to low cooling load. There is good matching between the specific useful net collector output of this study and Eicker et al. (2014).

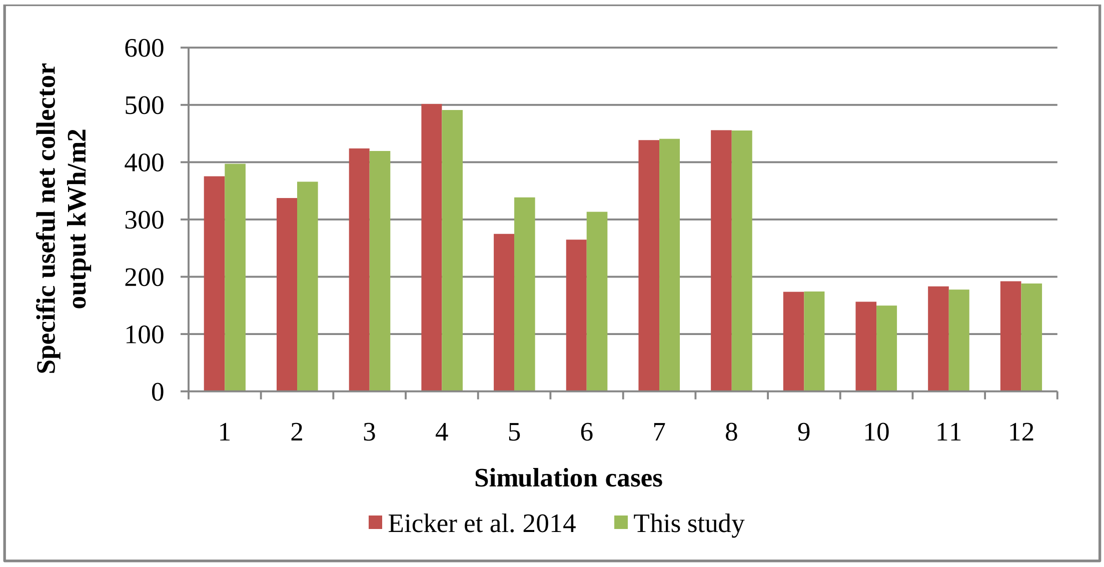


Fig. 4.6 Specific useful net collector output

4.2.6 Monthly model validation

Fig. 4.7 shows the cooling demand for Case No. 3 corresponding to Palermo city type 3 building without sun protection. It is clear from the fig.4.7 that cooling demand exists from April to November. Table 4.3 shows the values of error in the simulated cooling demand. It has been observed that the cooling demand has good agreement with the cooling demand of Eicker et al. (2014) with a mean bias error (MBE) of 0.05% and coefficient of variance (CV) is 0.1025.

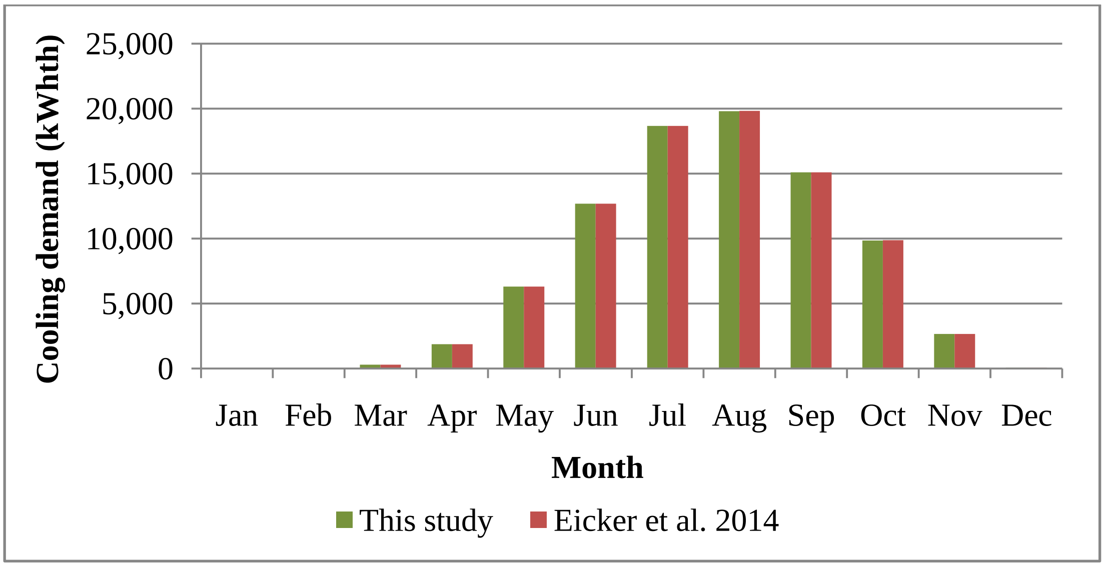


Fig. 4.7 Monthly cooling demand for Case No.3

Table 4.3 Cooling demand

Month	Cooling Demand (This study)	Cooling Demand (Eicker et al.)	Error	Square Error
January	17	17	0	0
February	52	52	0	0
March	323	323	0	0
April	1,883	1,884	1	1
May	6,325	6,326	1	1
June	12,701	12,703	2	4
July	18,662	18,670	8	64
August	19,809	19,833	24	576
September	15,096	15,100	4	16
October	9,872	9,875	3	9
November	2,668	2,669	1	1
December	98	98	0	0
Total	87,506	87,550	44	672

$$MBE(\%) = \frac{\sum(M - S)_{monthly}}{\sum M_{monthly}} \times 100 \quad (4.1)$$

$$= \frac{44}{87550} \times 100 = 0.05$$

$$RMSE = \sqrt{\frac{\sum_{month}(M - S)^2}{N_{month}}} \quad (4.2)$$

$$RMSE = \sqrt{\frac{672}{12}} = 7.48$$

$$A_{month} = \frac{\sum_{year} M_{month}}{N_{month}} \quad (4.3)$$

$$A_{month} = \frac{87550}{12} = 7296$$

$$CV = \frac{RMSE_{month}}{A_{month}} \times 100 \quad (4.4)$$

$$CV = \frac{7.48}{7296} \times 100 = 0.1025$$

Fig. 4.8 shows the monthly solar heat production and it is clear that the solar heat production is high from April to November due to high global radiation and it makes favorable condition for us because at the same time the cooling load is also high. The mean bias error calculated is 2% and CV is 2.17%. Table 4.4 shows the monthly solar heat production.

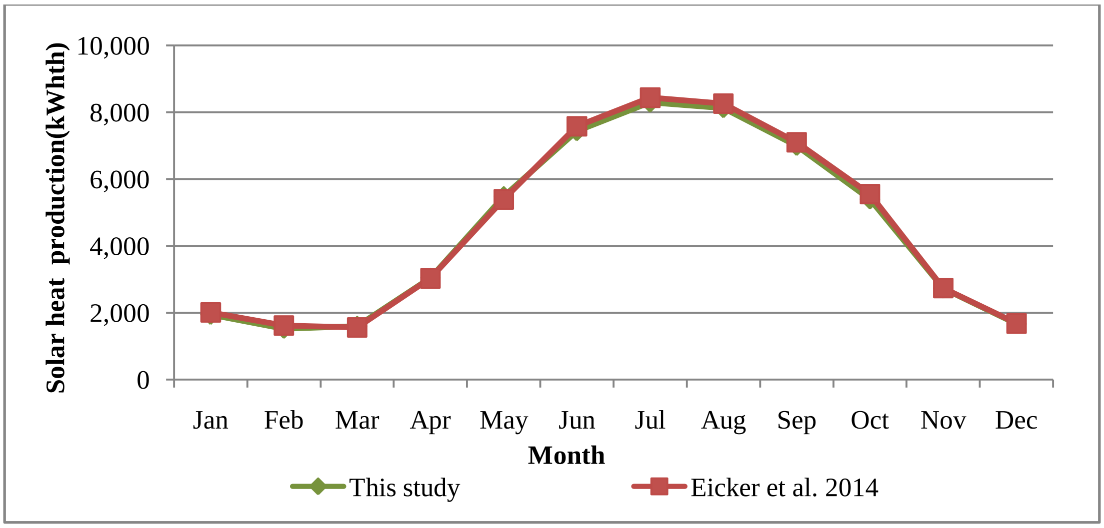


Fig 4.8 Solar heat production

Table 4.4 Solar heat production (MBE= 2% RMSE=99.58 CV= 2.17%)

Month	Solar Heat Production (This study)	Solar Heat Production (Eicker et al.)	Error	Square Error
January	1,939	2,009	70	4,900
February	1,525	1,621	96	9,216
March	1,595	1,562	-33	1,089
April	3,046	3,031	-15	225
May	5,485	5,397	-88	7,744
June	7,437	7,583	146	21,316
July	8,297	8,442	145	21,025
August	8,130	8,261	131	17,161
September	7,000	7,108	108	11,664
October	5,397	5,553	156	24,336
November	2,728	2,739	11	121
December	1,668	1,682	14	196
Total	54,247	54,988	1,013	118,993

The solar heat produced by the solar collector is supplied to the generator of the absorption cooling system and cooling is produced. Fig. 4.9 shows the monthly absorption cooling for the simulated system and it is good matched with Eicker et al. (2014). The mean bias error for the absorption cooling is calculated as 5.78% and CV is 8.95%. To fulfill the remaining amount of cooling an electric based compression chiller is provided in the system and Fig. 4.10 shows the monthly data of this compression cooling system. It has been observed from Figures 4.9 and 4.10 that when the absorption cooling part is low then the compression based cooling is high or vice versa to complete the cooling demand of the building. The mean bias error in the compression based cooling system is observed as 4.02% and CV is 6.27%.

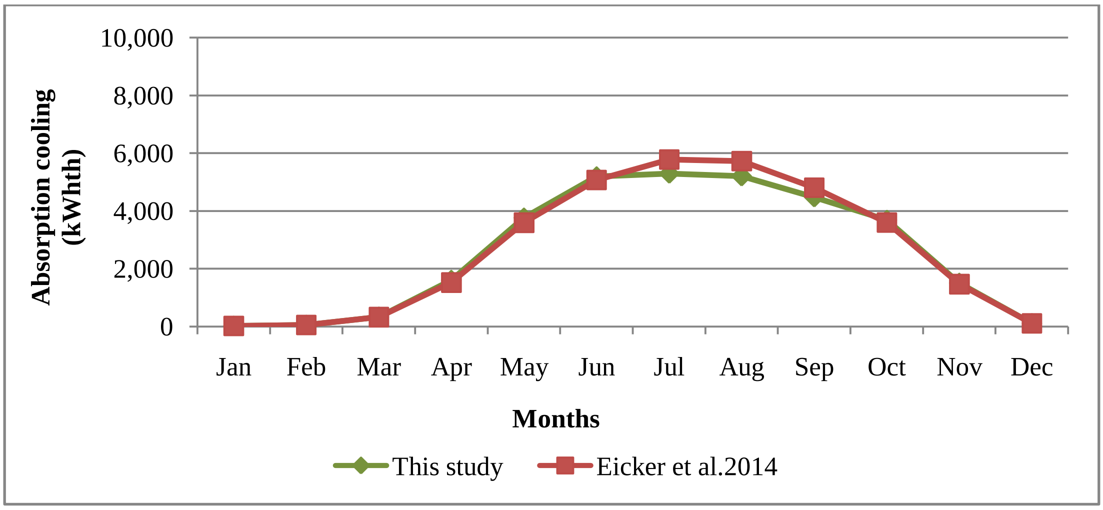


Fig. 4.9 Solar Absorption Cooling

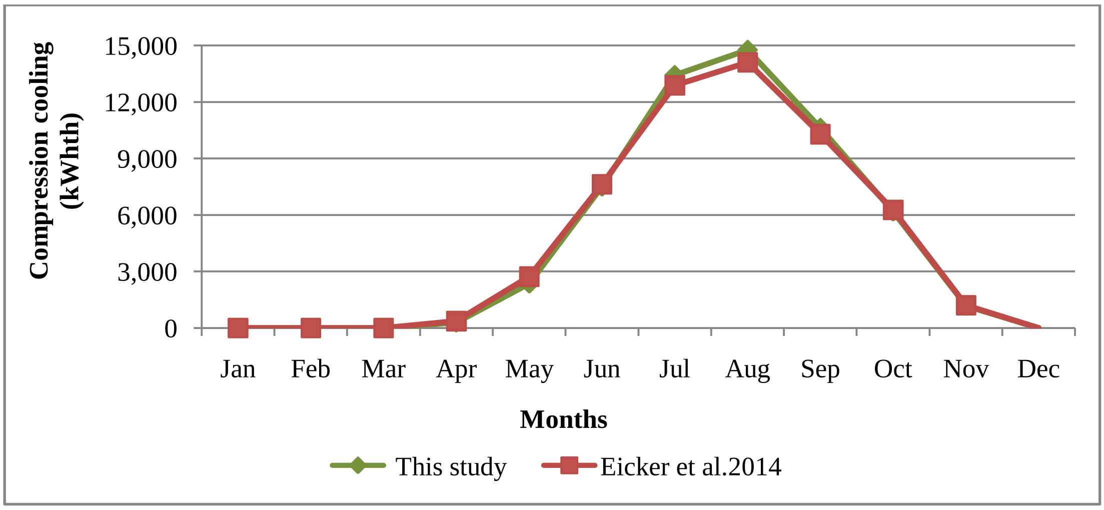


Fig. 4.10 Electric Compression Cooling

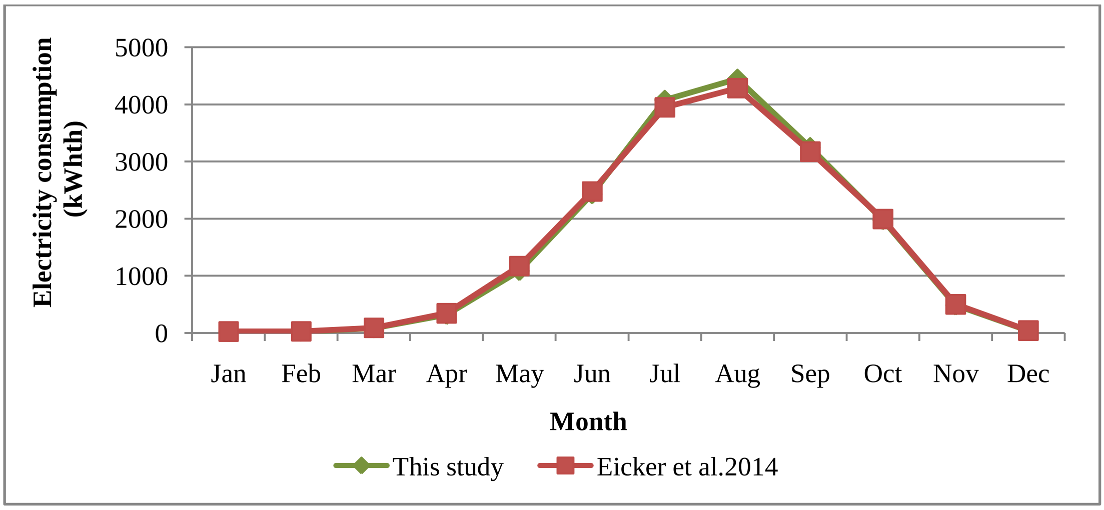


Fig. 4.11 Annual Electricity Consumption

Fig. 4.11 shows the total electricity consumption of the building for cooling including the electricity consumption by pumps and electric consumption of auxiliary cooling. It has been observed from Fig. 4.11 that the electricity consumption is matched with Eicker et al. (2014). The mean bias error and CV is calculated as 3.19% and 4.67% respectively.

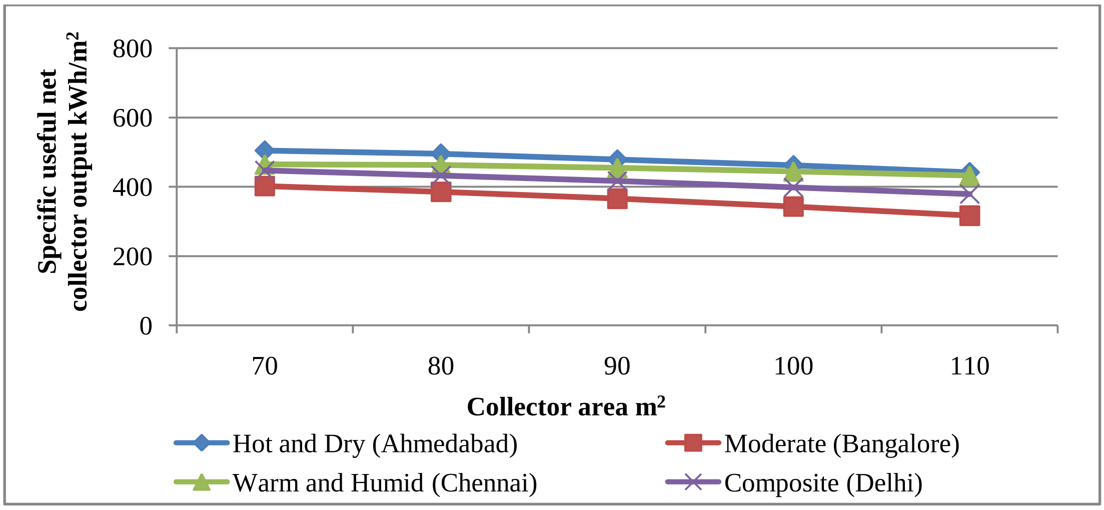
4.3 Performance Analysis of Solar Thermal Collector

In this section specific useful net collector output and net collector efficiency linking the performance of solar thermal collector are presented and disscudded.

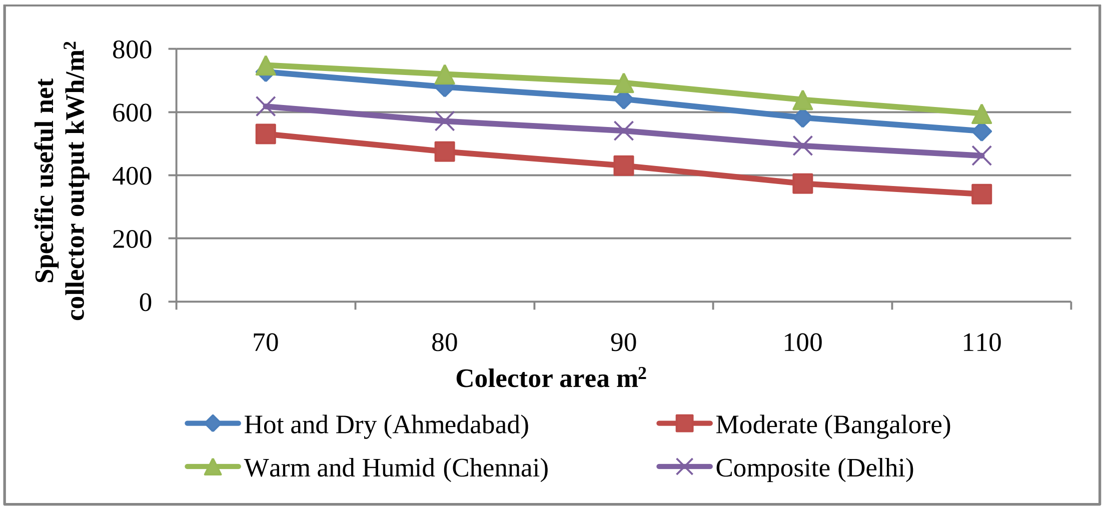
4.3.1 Specific useful net collector output

Specific useful net collector output is defined as the annual useful heat produced by the collector per unit area. Fig 4.12 a, b and c show the variation of specific useful net collector output with collector area and it is clear from the fig.4.12 that as the collector area increases the specific output decreases for the same cooling demand and capacity of hot storage tank. The higher collector area can deliver more heat but the heat should be either stored in a hot storage tank with adequate capacity or utilized simultaneously by the absorption chiller by increasing the pump flow rate, but here the capacity of storage tank and cooling demand is fixed so the full utilization is not possible resulting in the drop in specific useful net collector output. The same trends are observed for all types of collector in all the considered climates.

In ETC and CPC the drop in specific useful net collector output is higher than FPC because the same collector area in ETC and CPC generate more heat while the storage tank capacity, pump flow rate and cooling demand remain same hence heat is not fully utilized in both ETC and CPC resulting in higher drops in the net output. The drops in specific useful net collector area are highest in the moderate climate (Bangalore) because of lowest cooling demand. The cooling demand of the warm and humid climate (Chennai) is highest that utilizes the higher collector area resulting in the lowest drop in specific useful net collector area.



(a)



(b)

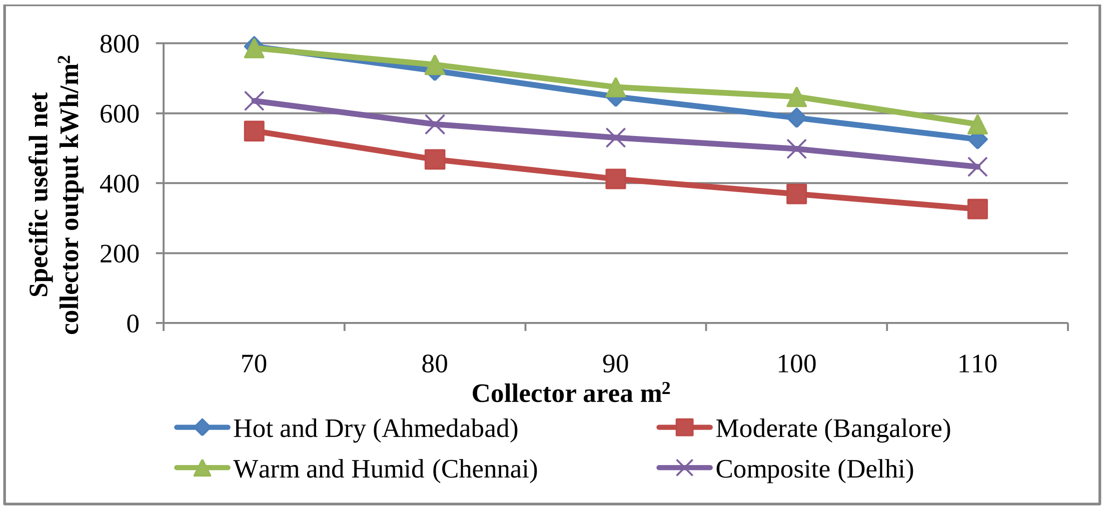


Fig.4.12 Variation of specific useful net collector output with collector area (a) FPC (b) ETC (c) CPC

Fig 4.13 shows the variation of specific useful net collector output, incident radiation on collector plane and annual cooling demand of the building in the considered climates. This graphic is for the flat plate collector having 90 m^2 collector areas for other collector areas results have been provided in Appendices. It has been observed that the highest specific useful net collector output 479 kWh/m^2 is for hot and dry climate (Ahmedabad) due to the good incident radiation 2176 kWh/m^2 as well as good cooling energy demand 195 kWh_{th}/m^2. In the moderate climate (Bangalore) the specific useful net collector output is very low, 365 kWh/m^2, due to low cooling energy demand 131 kWh_{th}/m^2 though the incident radiation is high. In the warm and humid climate (Chennai) the incident radiation 2039 kWh/ m^2 is lower than the composite climate (Delhi) 2166 kWh/m^2 but the specific useful net collector output is higher due to 45% higher cooling demand than the composite climate (Delhi). Building having higher cooling demand requires higher heat for generator of the solar thermal cooling system thus fully utilizes the collector heat resulting in higher specific useful net collector output.

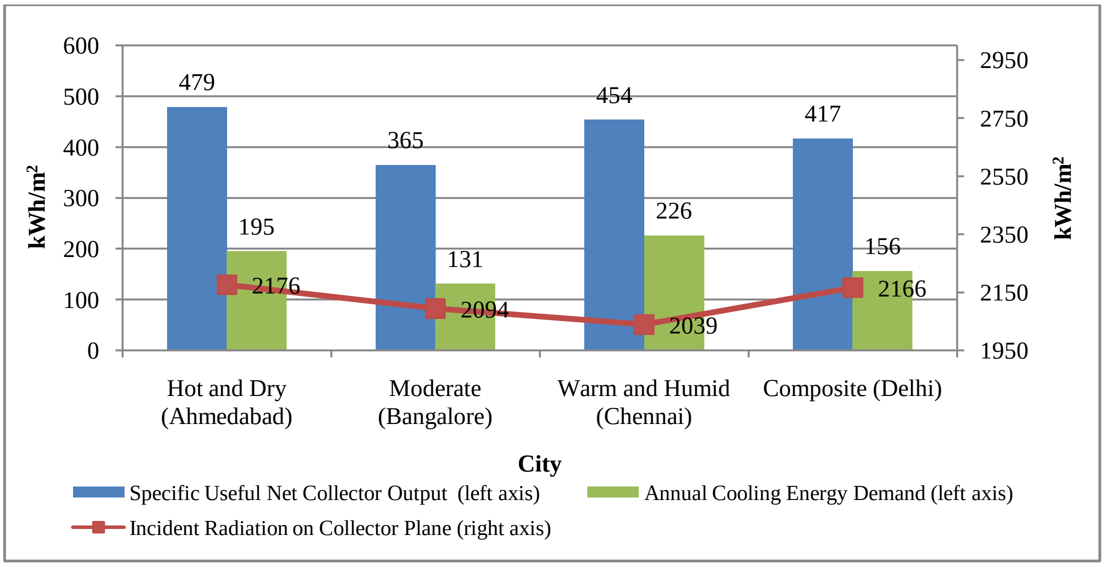


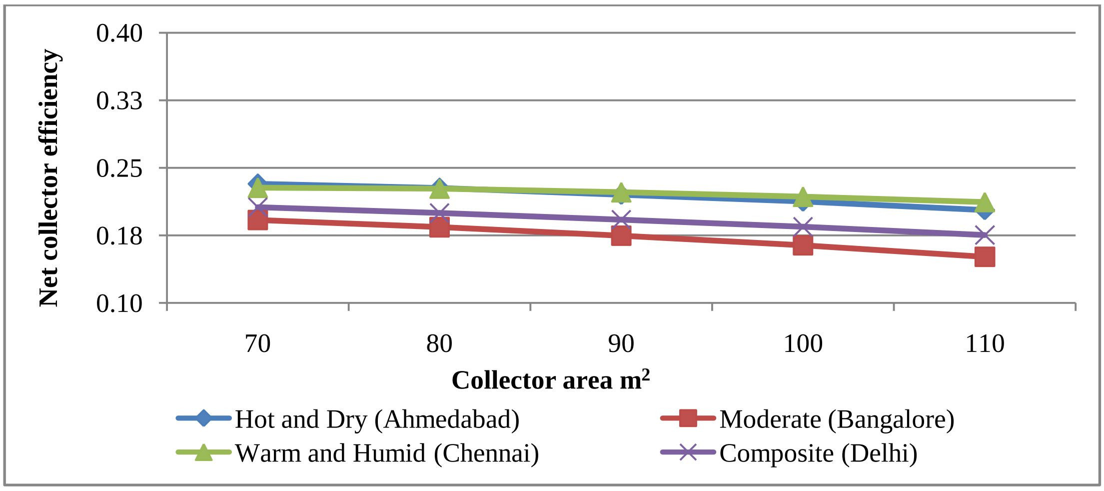
Fig 4.13 Specific useful net collector output (90 m^2 FPC)

4.3.2 Net collector efficiency

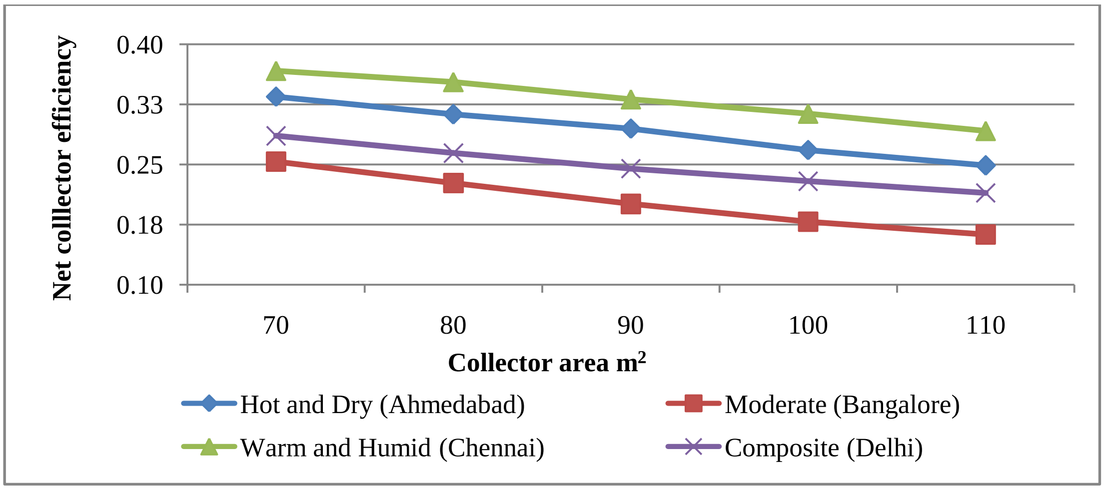
Net collector efficiency is the ratio of annual useful solar heat gain in working fluid to the annual incident radiation on collector plane. This is an indirect indicator that how much amount of heat is utilized by the solar thermal cooling system. Fig 4.15 (a) (b) and (c) show the net collector efficiency with the collector area for three types of collector and indicate that the net collector efficiency is lower for flat plate collector than the evacuated and compound parabolic type of collector. The highest efficiency is observed for the warm and humid climate (Chennai) and lowest for the moderate climate (Bangalore) because of the cooling energy demand i.e high in the warm and humid climate results better utilization of collected heat. In the moderate climate the cooling energy demand is low results in the low utilization of collected heat.

In the flat plate collector the difference between efficiency for all climates is lesser because the heat produced by collector is lesser so the system mostly immediately utilizes this heat in producing the cooling effect. The drop in net efficiency is also lower. In the warm and humid climate (Chennai) the net efficiency at 70 m^2 collector area is observed 23 % while at 110 m^2 it is 21% so only 2% drop in the efficiency is observed. While for moderate climate (Bangalore) the drop in the collector efficiency is 4%, hot and dry (Ahmedabad) 3% and composite climate (Delhi) 3%.

In the ETC and CPC more effect of cooling demand can be seen from the fig.4.15 b and c. We observe that the difference in efficiency is considerably higher depending on cooling demand in the climates. The drop in net collector efficiency for evacuated tube type collector is 8 % for the three climatic zones hot and dry, warm and humid and composite and 9% for moderate climate when the collector area is varied from 70 m^2 to 110 m^2.



(a)



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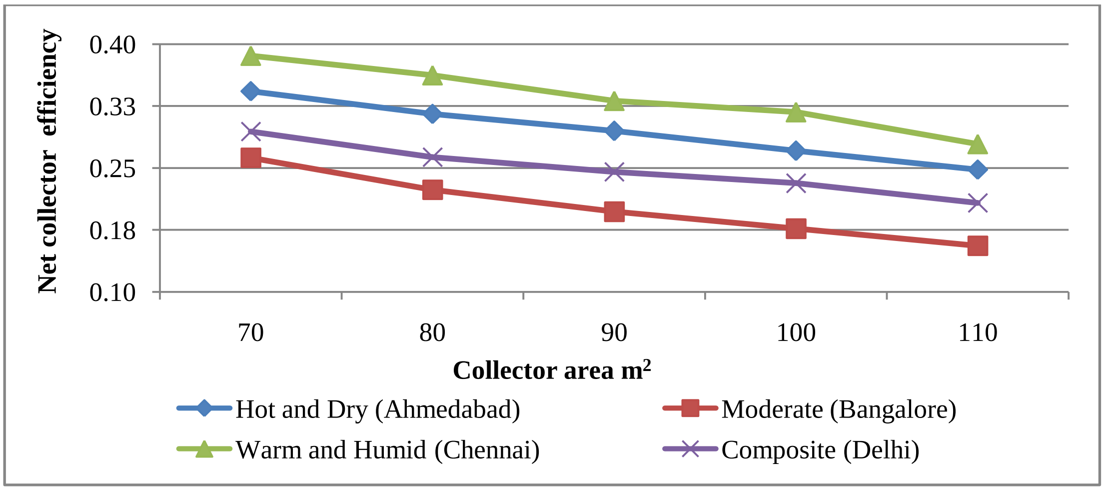


(c)

Fig 4.15 Variation of net collector efficiency with collector area

(a) FPC (b) ETC (c) CPC

4.4. Performance Analysis of System

In this section solar fraction, electrical (grid) COP of solar thermal cooling systems are presented and discussed.

4.4.1 Solar Fraction

It is the ratio of the annual cooling effect produced by the solar to the total annual cooling demand of the building.

$$\text{Solar Fraction} = \frac{\text{Annual cooling effect produced by solar absorption chiller}(\text{kWh}_{\text{th}})}{\text{Annual coling demand of building}(\text{kWh}_{\text{th}})} \qquad (4.5)$$

Fig 4.16 a, b and c shows the variation of solar fraction for different climates and various collector area of FPC, ETC and CPC respectively. It is clear from the fig 4.16 a that in FPC, as the collector area increases the solar fraction also increases because more heat is collected by the collector and supplied to the solar thermal cooling system that produce the more amount of solar cooling. The solar fraction is highest for the moderate climate (Bangalore) and lowest for the warm and humid climate (Chennai) in the range of collector area because the cooling demand of the building is 131 kWh_{th}/m^2 in the moderate climate is 42% less than the warm and humid climate while the solar radiation is 2094 kWh/m^2 in the moderate climate that is 2% more than the warm and humid climate.

At small collector area of 70 m^2 the annual heat production is low for all the cities and solar thermal cooling system produce the low amount of cooling and in this condition the solar fraction is 66% for moderate climate (Bangalore) due to low cooling demand and it is 59% for hot and dry climate (Ahmedabad), for warm and humid climate (Chennai) 51%, and for composite climate (Delhi) it is 63%. It is very low for the warm and humid climate (Chennai) because of the very high annual cooling demand, 225 kWh_{th}/m^2 and low incident radiation compared to other climates. As the flat plate collector area increase from 70 m^2 to 110 m^2 the solar fraction for all cities increases because more heat is collected by the collector but its effect will be much more if this heat is effectively utilized to produce the cooling effect. In the warm and humid climate (Chennai) the building cooling demand is very high and the heat is effectively utilized so change in solar fraction is higher with the increase in collector area than other cities. If the collector area is increased from 70 m^2 to 110 m^2 the solar fraction increases from 51 % to 71 % in warm and humid climate (Chennai), 59% to 75 % in hot and dry conditions (Ahmedabad), 66% to 77% in moderate climate (Bangalore) and 63% to 78 % in composite climate(Delhi).

Fig 4.16 b and c shows the variation of solar fraction for the evacuated type and compound parabolic type collector respectively. The solar fraction is highest for the CPC type collector and lowest for the FPC. In both type, ETC and CPC, out of the four climate the solar fraction is highest for the moderate climate and lowest for the warm and humid climate similar as in the FPC type.

The change in solar fraction with collector area is high in flat plate where it is low in ETC and CPC, due to high efficiency of ETC and CPC collectors that produce the higher heat even at lower collector areas for the same building cooling demand. It has been observed from the fig.4.16 that for flat plate collector the highest solar fraction occurs at 110 m^2 collector area in all considered climatic zones, in the case of ETC highest solar fraction is at collector area of 100 m^2 in the hot and dry climate (Ahmedabad), warm and humid climate (Chennai) and composite climate (Delhi) where as it is 90 m^2 for moderate climate (Bangalore). In the Bangalore city the cooling demand of the building is quite low in comparison to other cities so 90 m^2 collector area offers highest solar fraction beyond this collector area, more collector losses and result into decrease in the solar fraction. In the case of CPC highest solar fraction occurs in the hot and dry (Ahmedabad) and warm and humid climate (Chennai) at 90m^2 collector area, for moderate (Bangalore) it is 70m^2 and for composite climate (Delhi) it is 100 m^2.

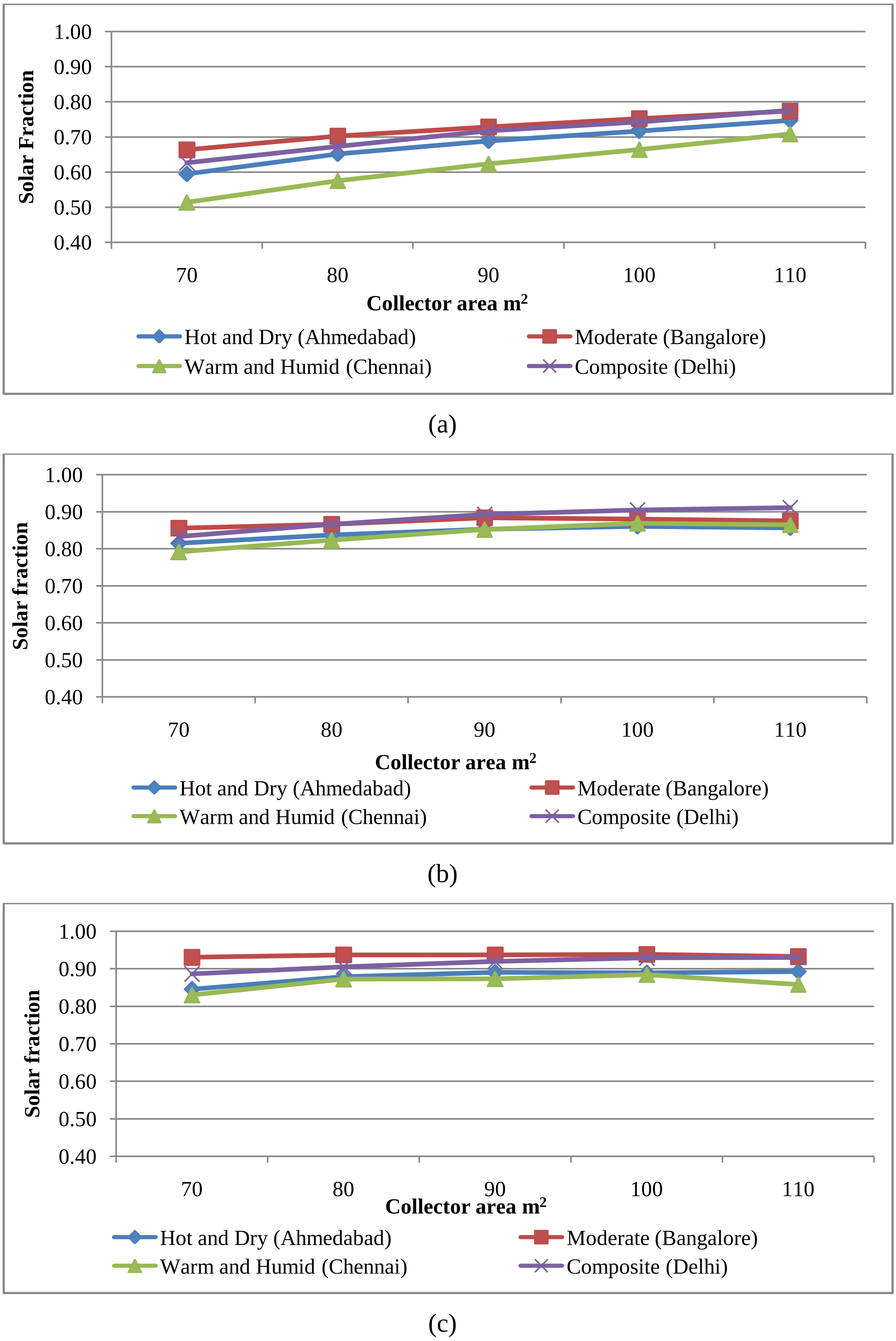


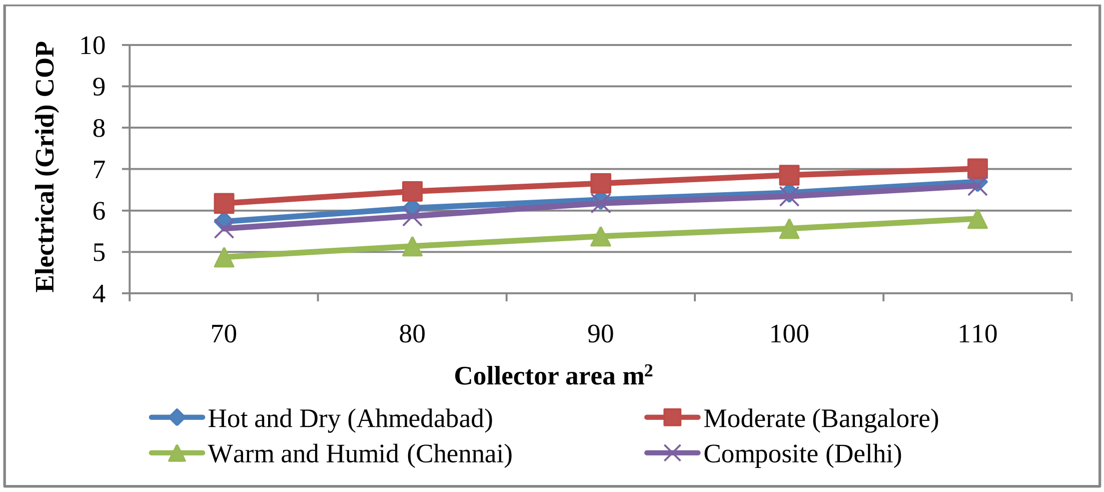
Fig 4.16 a-c Variation of solar fraction with collector area

(a) FPC (b) ETC (c) CPC

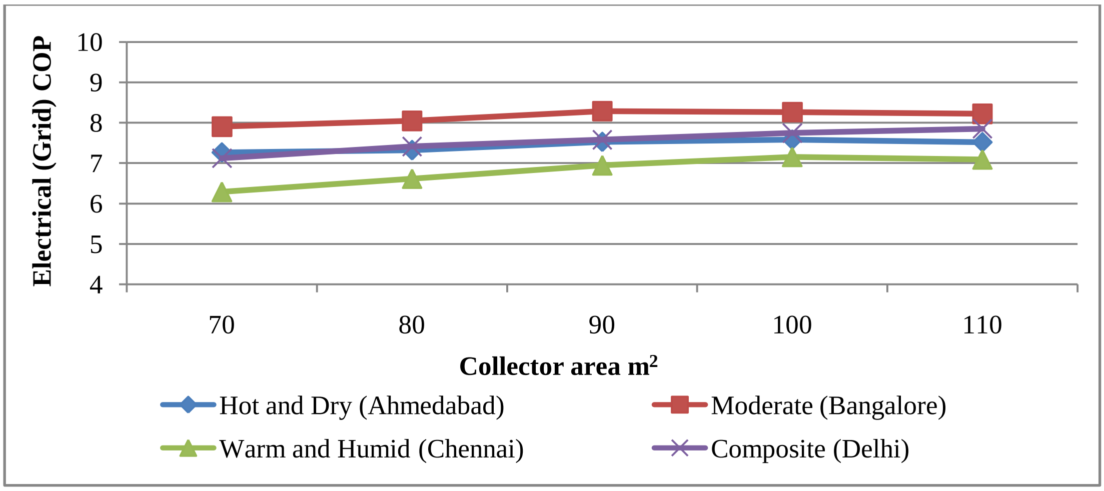
As the collector area increases the solar fraction also gets increased but after an optimum collector area it starts decreasing because at elevated temperature heat losses are also higher. If we use a high collector area then we have to increase either the capacity of storage tank or the cooling demand of the building otherwise there will be no effect of collector area after an optimum value. The highest solar fraction has been observed as 0.89, 0.94, 0.88, and 0.93 for hot and dry, moderate, warm and humid and composite climate respectively.

4.4.2 Electrical (Grid) COP of system

The electrical COP (Grid) of the solar thermal cooling system is defined as the ratio of annual cooling demand of the building divided by the annual consumption of electrical energy drawn from the grid and consumed by all the system including pumps, cooling tower and backup chiller. This term excludes the energy coming from solar collector. Value of this term is higher for any system having higher solar fraction. Fig 4.17 a-c show the variation of electrical COP of the system with the collector area. It has been observed from the fig.4.17 that the electrical COP of the system increases with the collector area in all types of collectors. For the flat plate type collector the electrical COP of the system is less than the evacuated tube and compound parabolic type collector because flat plate collector has lower efficiency resulting in the low heat production for the same absorber area coupled with the same building cooling load. In the moderate climate (Bangalore) the annual cooling demand of the building is 30,000 kWh_{th} very less in comparison to others and the radiation is quite high so the production of heat is good resulting in better electrical COP (grid) of the system. In the warm and humid climate (Chennai) the cooling demand is higher 51000 kWh_{th} and the radiation is lower 2039 kWh/m^2 so the production of heat is lower and solar cooling produced is lesser hence remaining cooling demand is fulfilled by the electrical chiller used for backup that enhances the electrical energy consumption and lowers the COP of the system.



(a)



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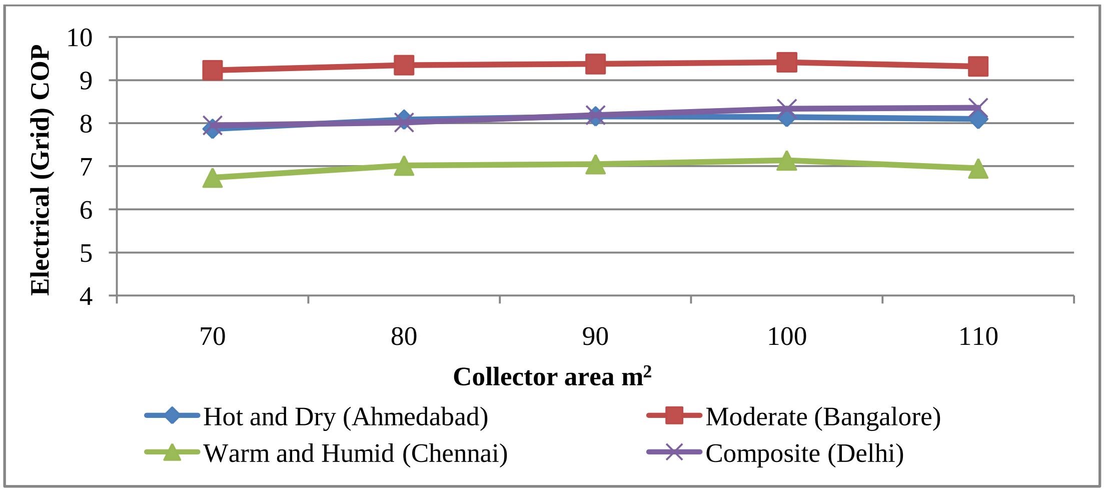


(c)

Fig 4.17 a-c Variation of electrical COP (Grid) of the system with collector area (a) FPC (b) ETC(c) CPC

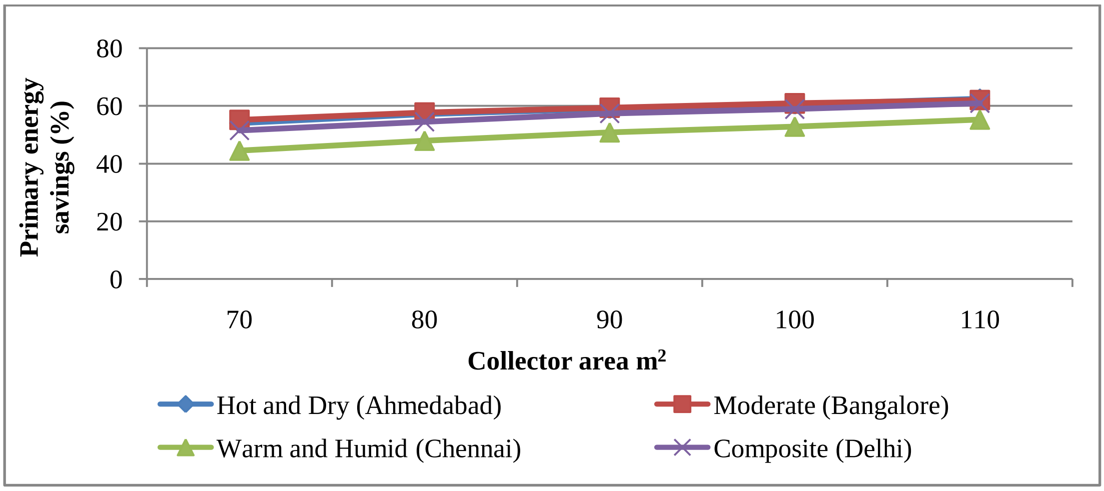
4.5 Energy and Economic Analysis

In this section primary energy savings, specific primary energy savings, payback period and cost per unit of primary energy saved are presented and discussed related to energy and economic performance of solar thermal cooling system.

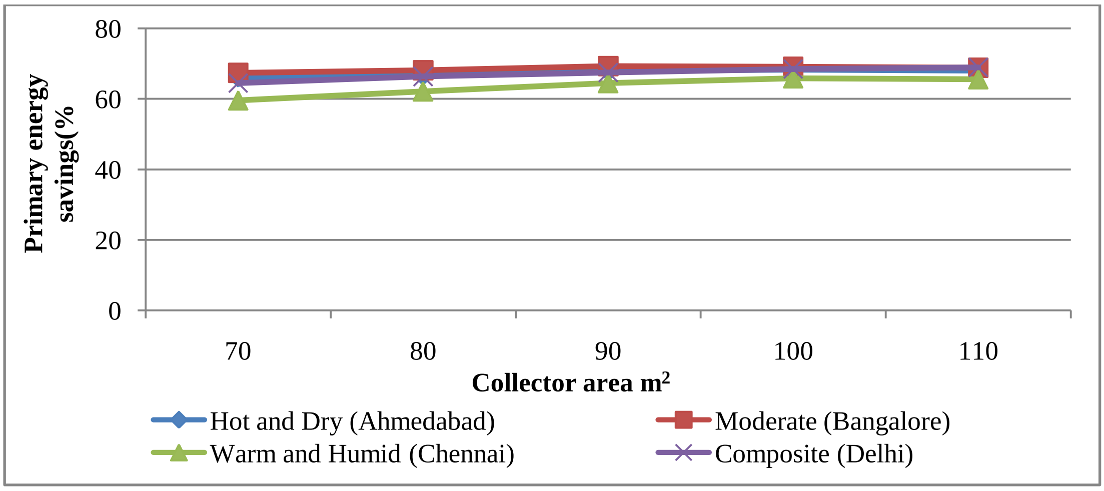
4.5.1 Primary Energy Savings

Primary energy is an energy form found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels. Primary energy consumption is calculated from energy consumption of the cooling systems by dividing it to the conversion factor 0.36 [Eicker et al.]. In the solar thermal cooling system the electrical energy is consumed by pumps, controls and electrical chiller used as a backup. In the solar photovoltaic cooling system the electrical consumption is due to running of compressor, condenser fan and blower. The primary energy savings is the difference between the primary energy consumption by the solar thermal cooling system and the primary energy consumption by the compression based cooling system operated by grid power.

Fig 4.18(a) (b) and (c) shows the variation in primary energy savings with different collector areas. It is observed from the fig. 4.18 (a) that the primary energy savings are increased with the increase in collector area (FPC), despite reduction in collector efficiency because more heat is collected by the solar thermal collector for the same cooling demand. The primary energy savings are higher for the moderate climate (Bangalore) 55-62 % and lowest for the warm and humid climate (Chennai) 44-55%. It is between 54- 62 % for the hot and dry climate (Ahmedabad) and 51 - 61 % for the composite climate (Delhi). The primary energy savings are highest for moderate climate due to very low cooling demand of 131 kWh_{th}/m^2 and the primary energy savings are lowest for the warm and humid climate (Chennai) because of the very high cooling demand of 225 kWh_{th}/m^2.



(a)



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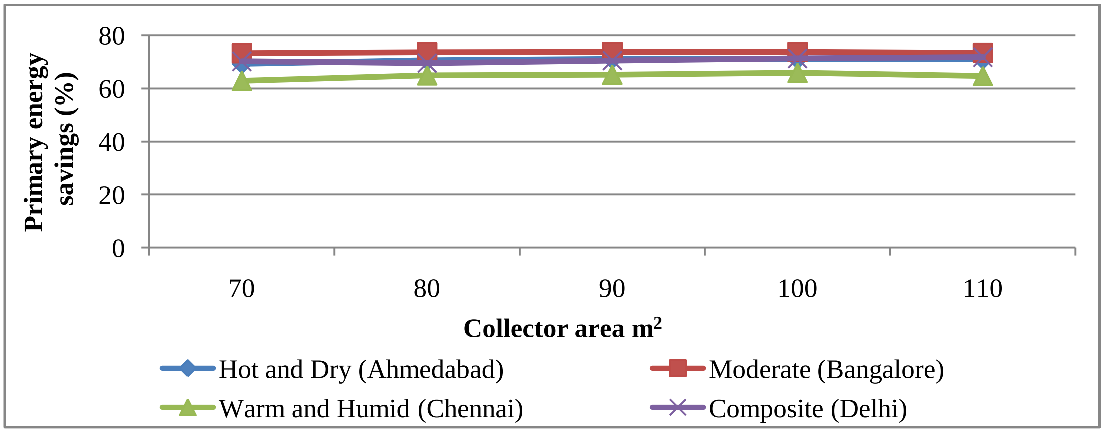


(c)

Fig.4.18 Variation of primary energy savings with collector area

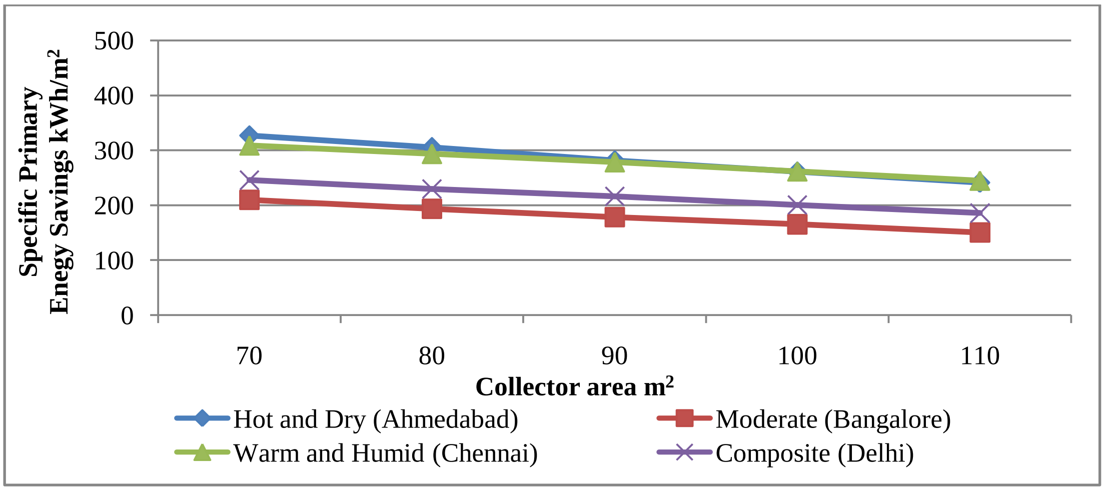
(a) FPC (b) ETC (c) CPC

Fig 4.18 b and c shows the variation of primary energy savings for the evacuated type collector with the collector area. It is observed from the fig.4.18 that as the collector area increases the primary energy savings also increase similar to the FPC. The change in the primary energy savings in the ETC and CPC type collector is very low in comparison to the FPC because in the case of ETC and CPC even the low collector area produce the higher heat in comparison to the FPC and saved the higher primary energy savings. At high collector area the collected heat is increased in all the type of collector but in the case of ETC and CPC the heat losses also increase, so with the increase in the collector area the increment in the primary energy savings are higher for the FPC and lower for the ETC and CPC. In the ETC and CPC after an optimum collector area the primary energy savings gets decreased. For the same cooling machine type, capacity and building cooling load increase in collector area does not produce much effect in case of primary energy savings. The highest primary energy savings is 71.05% for hot and dry climate (Ahmedabad), 73.74% for moderate climate (Bangalore), 65.86% for warm and humid (Chennai) and 71.70% for the composite climate (Delhi).

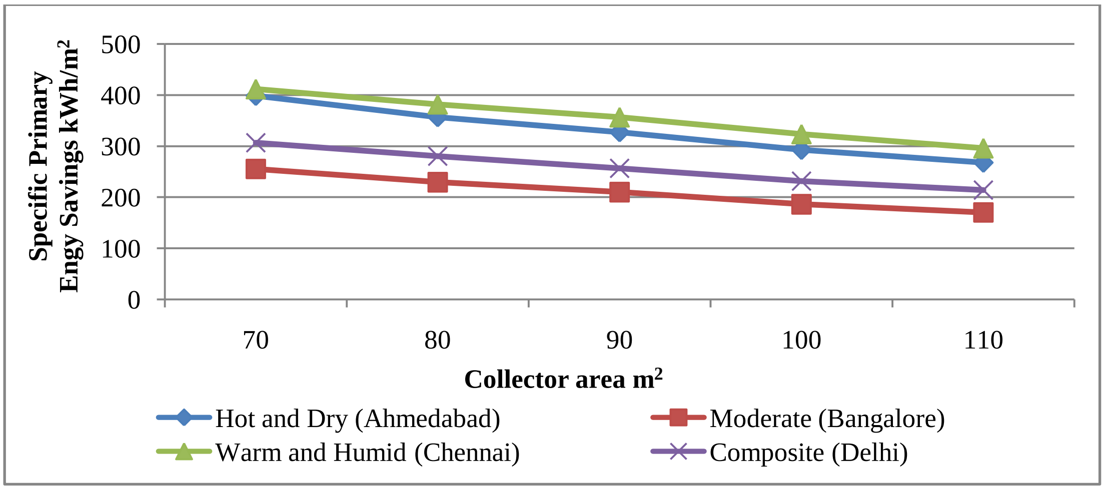
4.5.2 Specific primary energy savings

Specific primary energy savings are defined as the primary energy savings per unit collector area. Fig 4.19 (a), (b), and (c) show the specific primary energy savings for the three types of collector. It has been observed from the fig.4.19 that the specific primary energy savings are higher at lower collector area but its value decreases as the collector area is increased for all types of collector and climate because the efficiency of solar collector decreases as the area increases. Fig 4.19 a shows that the specific primary energy savings are highest at 70 m^2 collector area for the hot and dry climate (Ahmedabad) because of the high cooling demand of the building and high solar radiation. For warm and humid climate (Chennai) the building cooling demand are higher but at the same time the intensity of solar radiation is lesser than the hot and dry (Ahemdabad) so specific primary energy savings are also lesser. In the moderate climate (Bangalore) the specific primary energy savings are less because of the low cooling demand. As we increase the collector area the value of primary energy savings become higher for the warm and humid climate (Chennai) than the hot and dry climate (Ahemdabad) because in the latter at higher collector area the heat loss is also higher due to higher ambient temperature.

Evacuated tube and compound parabolic type collectors have higher specific primary energy savings than the flat plate collector because the higher efficiency and lesser heat loss of the both. For hot and dry climate (Ahmedabad) the specific primary energy savings is 327, 398 and s 429 kWh/m^2 for the FPC,ETC and CPC respectively using the same collector area of 70 m^2. For the same collector area the specific primary energy savings in the moderate climate (Bangalore) are 186, 210 and ,255, kWh/m^2, in the warm and humid climate (Chennai) 309, 411 and 447 kWh/m^2 and in the composite climate (Delhi) 246, 307 and 344 kWh/m^2 using FPC, ETC and CPC respectively. The highest specific primary energy savings are achieved by using the compound parabolic collector. In the warm and humid climate (Chennai) cooling demand is highest so the highest value of specific primary energy savings of 447 kWh/m^2 are achieved with the compound parabolic collector having 70 m^2 area.



(a)



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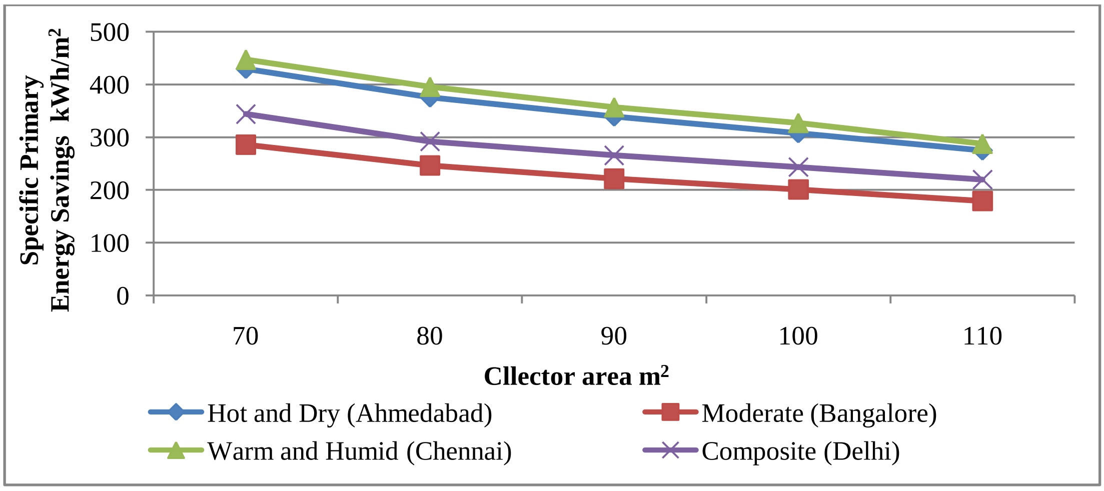


(c)

Fig 4.19 Variation of specific primary energy savings with collector area (a) FPC (b) ETC (c) CPC

4.5.3 Economic analysis

To plan any energy project such as solar cooling systems, economic consideration form the basis for decision making. All the cost over the entire life cycle can be grouped into three categories: capital costs, which contain the major equipment cost including installation, maintenance cost and operating cost for the cost of energy and other material inputs in the system. It is assumed that in India, there is no demolition cost. Table 4.5 shows the cost of the components associated with the solar thermal cooling and reference system.

Table 4.5 Cost and parameters considered in the calculation

S.No.	Component	Size	Unit	Price	Source
1	Solar collector –FPC	70- 110 m^2	Rs/m^2	6250	Sunwas Energy savings systems Jaipur
2	Solar collector –ETC	70- 110 m^2	Rs/m^2	9300	Mamta Energy Gujarat
3	Solar collector –CPC	70- 110 m^2	Rs/m^2	13500	Orja Energy Engg services Hyderabad
4	Hot Storage Tank -HST	5 m^3	Rs	400000	Metasis Engineering Pune
5	Compression Chiller	10.5kW	Rs	280000	Arh Technology Pvt.Ltd
6	Packaged Air Conditioner VRF	35 kW 24.5kW 35kW	Rs Rs Rs	500000 350,000 800,000	Climatech Aircon Engineering Pvt. Ltd. Jaipur
7	Absorption Chiller	35 kW 24.5kW	Rs Rs	1800000 1260000	Mamta Energy Gujarat
8	Cold storage tank	1 m^3	Rs	50000	Metasis Engineering Pune
9	Cooling tower	85 kW	Rs	62500	Advances Cooling Tower Pvt Ltd. Mumbai
10	Pump	1Nos.	Rs	25000	Climatech Jaipur
11	Discount rate (Interest rate)	-	-	8%	State Bank of India, 2014
12	Yearly maintenance cost of solar	-	-	1%	Hartmann et al. (2011)
13	Yearly maintenance cost of other component	-	-	1.50%	
14	Electricity Rate(Average for all considered cities)	-	Rs/kWh	7.55	Central electricity authority Delhi
15	Expected life time solar component	-	Years	20	Elasifi (2002) , Tscotous(2010)
16	Expected life time Compression System	-	Years	8	Elasifi (2002), Tscotous(2010)
17	Conversion factor electricity	-	kWhel/kWh primary energy	0.36	Calculated Appendix :E

Capital cost

The capital cost is one time investment for any project. It is composed of the sum of all the components of every system. The cost of component is calculated by multiplying the size of each component by its specific cost as shown in the table 4.5. In some cases the fixed valued are also considered. Fig 4.20 shows the capital cost of the all the climates except moderate. The capital cost of the system having the flat plate collectors are lower and increases with the collector area. System having the compound parabolic collectors have the highest investment cost among all of them. Since the reference system does not have influence of the thermal collector area so the cost of the reference system is constant irrespective of the collector area. The same systems are used in hot and dry, warm and humid and composite climates so the capital cost for these are equal. In the moderate climate the size of absorption chiller is 7 TR accordingly the total annual cost is reduced. Similary in moderate climate the cost of reference system is 3.5 Lac.

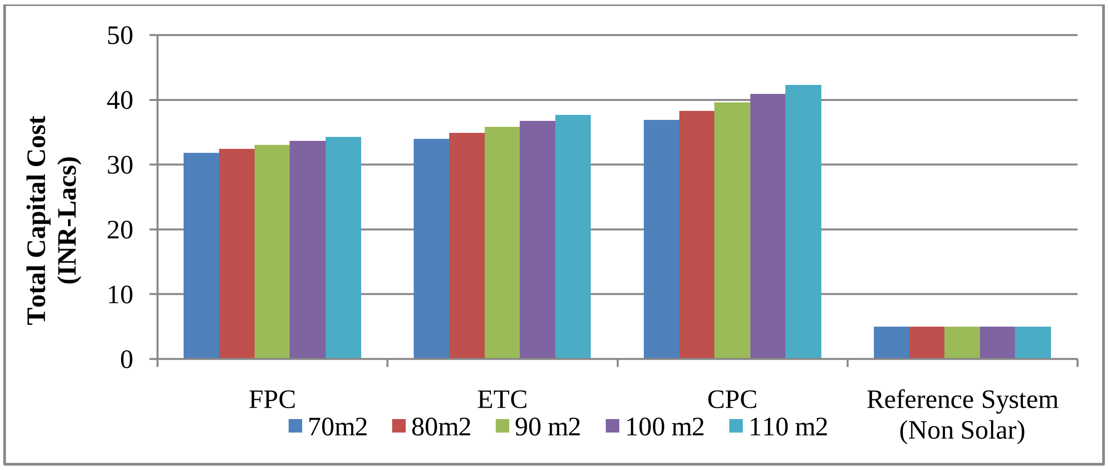


Fig.4.20 Capital costs with collector area

The following parts show the calculation for the investment cost of the system having the thermal collector area of 90 m^2.

1. Solar thermal collector (FPC) = 6250 Rs/m^2 × 90 m^2 = 562500 INR
2. Solar thermal collector (ETC) = 9300 Rs/m^2 × 90 m^2 = 8370000 INR
3. Solar thermal collector (CPC) = 13500 Rs/m^2 × 90 m^2 = 1215000 INR
4. Hot storage tank (solar thermal system) = 400000 INR
5. Cold storage tank (solar thermal system)= 50000 INR
6. Absorption chiller (Solar thermal system-10TR) = 1800000 INR
7. Compression Chiller (backup for thermal solar system) = 280000 INR
8. Packaged Air Conditioner (Reference system-10TR) = 500000 INR

9. Pumps (Solar thermal system) = 25000×6 = 150000 INR

10. Cooling tower (Solar thermal system) = 62100 INR

11. Total investment cost (Solar thermal system) = (solar thermal collector cost + hot storage tank + absorption chiller +compression chiller + cold storage tank + cooling tower + pumps)

11 a. Total investment cost (Solar thermal system- FPC) = 3304600 INR

11 b. Total investment cost (Solar thermal system- ETC) = 3579100 INR

11 c. Total investment cost (Solar thermal system- CPC) = 3957100 INR

11 d. Total investment cost (Solar thermal system-moderate-FPC) = 2764000 INR

12. Total investment cost (Reference system) = 500000 INR

12a. Total investment cost (Reference system-moderate) = 350000 INR

Annual maintenance and operation cost

This cost is considered as the annual expenses on the maintenance and operation during a year in routine. The maintenance cost is considered as 1% for solar and 1.5 % for non solar components [Tscotous 2010]. The operative expenses include the cost of electricity consumption by the pumps and backup chillers in the solar thermal cooling system and for reference system it is the cost of electricity consumption by compression based air conditioner. The cost of electricity is taken as INR 7.55/kWh that is the average cost of electricity in the considered climates [CERC]. Fig 4.21shows the annual maintenance cost of both the solar thermal cooling system and for reference. The cost of maintenance is the same for all the considered climates with same system and varies with the type of collector and area. Since the reference system does not have influence of the thermal collector area so the maintenance cost for the reference system is constant irrespective of the collector area. The cost of maintenance for moderate climate is different than others because of the sizing and cost of absorption chiller.

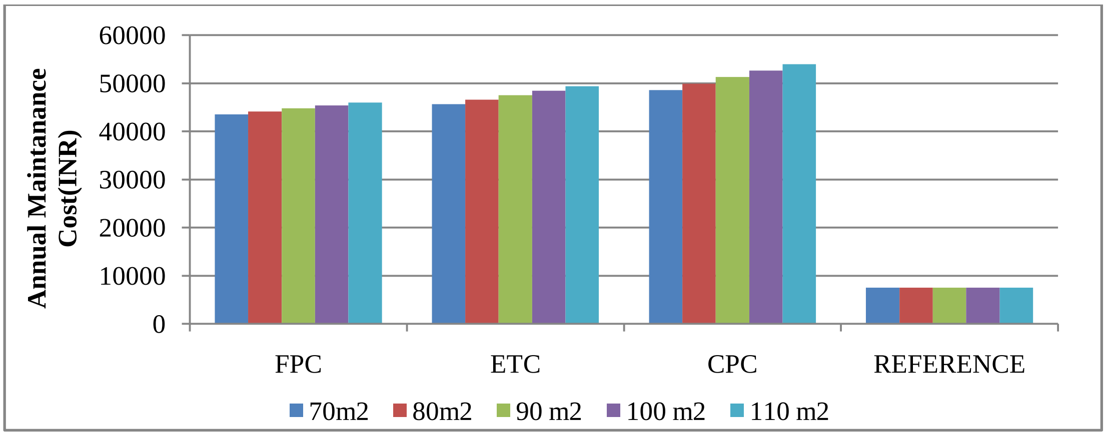


Fig.4.21 Annual maintenance cost with collector area

The calculation for the maintenance cost of the system having the thermal collector area of 90 m^2 is as follows:

1. Maintenance cost = 1% × (Investment on solar component) + 1.5 % × (Investment cost of other components)
2. Maintenance cost (FPC) = 1% ×[562500+400000] + 1.5% ×[3304600-562500-400000]= 9625+35131= 44756 INR
3. Maintenance cost (ETC) = 1% ×[837000+400000] + 1.5%× [3579100-837000-400000]= 12370+35131= 47501 INR
4. Maintenance cost (CPC) = 1% ×[1215000+400000] + 1.5% ×[3957100-1215000-400000]= 16150+35131= 51281 INR
5. Maintenance cost (Reference) = 1.5% ×[500000] = 7500 INR

The calculation for maintenance cost of the solar thermal cooling system in moderate climate having FPC with 90m^2 is as.

1. Maintenance cost (FPC) = 1% ×[562500+400000] + 1.5% ×[2764600-562500-400000]= 9625+270311= 36656 INR
2. Maintenance cost (Reference-moderate) = 1.5% ×[350000] = 5250 INR

The operation cost for the solar thermal cooling system is calculated by the cost of electricity per kWh multiplied by the annual consumption of electricity. As the collector area increases the operation cost decreases due to low electricity consumption. In the warm and humid climate the cooling demand of the building is high so annual electricity consumption is also high. In the reference the operation cost is the cost of electricity consumption by the packaged air conditioner.

The following parts show the calculation for the operation cost of the system for the hot and dry climate with the flat plate collector area of 90 m^2.

1. Annual electricity cost (consumption) = annual total electricity consumption × electricity cost
2. Annual electricity cost (FPC) = 6409 kWh ×7.55 Rs/kWh = 48385 INR
3. Annual electricity cost (ETC) = 5003 kWh ×7.55 Rs/kWh = 37774 INR
4. Annual electricity cost (CPC) = 4523 kWh ×7.55 Rs/kWh = 34148 INR
5. Annual electricity cost (Reference) = 15618 kWh ×7.55 Rs/kWh = 117916 INR

Total annual cost

The analysis presented here is based on the annuity method, where all the cash flows connected with the solar cooling installation and reference system are converted into the annual payments of equal amount using the annuity factor. Fig 4.22 shows the total annual cost of the considered climate with different types of collector having the same area of 90 m^2. Total annual cost includes the fraction of capital cost converted by the annuity method, annual maintenance cost and annual electricity consumption cost. Here the annual capital cost and annual maintenance cost are similar for all climates except moderate and the annual consumption on electricity is different depending on the cooling demand and solar fraction. It is clear from the fig. 4.22 that the total annual cost for the warm and humid climate (Chennai) is highest having the highest cooling demand and lowest for moderate climate (Bangalore) having the lowest cooling demand. The same trends are observed for the reference system. Table 4.6 shows the total annual cost in the considered climates and collector area. It is clear that the total annual cost increases with the collector area in all the climates and highest for the CPC type collector. In the reference system total annual cost is constant irrespective of collector type and area but it varies with the climate.

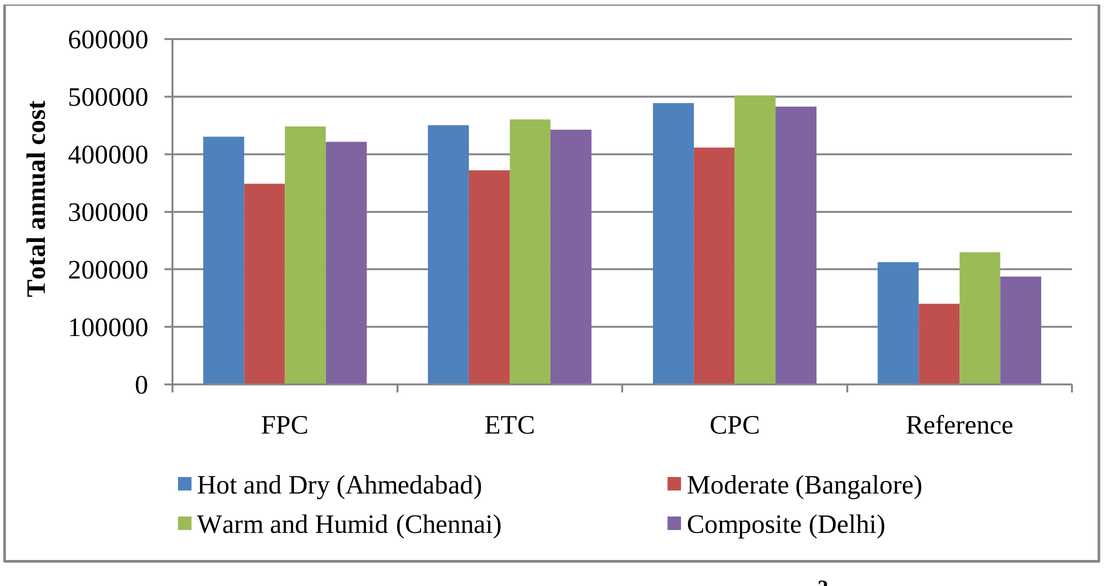


Fig 4.22 Annual cost (Collector area 90 m^2)

Table 4.6 Total annual cost

FPC						
	70 m^2	**80 m^2**	**90 m^2**	**100 m^2**	**110 m^2**	**Reference**
Hot and Dry (Ahmedabad)	422026	425359	430212	435470	440117	212416
Moderate (Bangalore)	337912	343017	348795	354685	360820	140329
Warm and Humid (Chennai)	442862	445234	448375	452664	456317	229736
Composite (Delhi)	413025	417211	421502	427137	432195	187599
ETC						
Hot and Dry (Ahmedabad)	431638	441454	450345	460316	471056	212416
Moderate (Bangalore)	352724	362593	372123	382692	393290	140329
Warm and Humid (Chennai)	446396	453320	460561	469093	479954	229736
Composite (Delhi)	424765	433460	442816	452318	462293	187599
CPC						
Hot and Dry (Ahmedabad)	460949	474514	489054	504182	519451	212416
Moderate (Bangalore)	381356	396171	411273	426322	441739	140329
Warm and Humid (Chennai)	474984	487273	502047	516200	532968	229736
Composite (Delhi)	452436	468202	482428	496809	511489	187599

The following parts show the calculation for the annual cost of the system having the flat plate collector area of 90 m^2 in the hot and dry climate.

1. Annuity factor $= \frac{i \times[(1+i)^n]}{[(1+i)^n - 1)]}$ (4.6)

   Where i interest rate, n = lifetime of the system or component

2. $\text{Annuity factor (solar thermal system)} = \frac{0.08\times[(1+0.08)^{20}]}{[(1+0.08)^{20}-1)]} = 10.2$
3. $\text{Annuity factor (reference system)} = \frac{0.08\times[(1+0.08)^{8}]}{[(1+0.08)^{8}-1)]} = 17.4$
4. Capital cost = annuity factor × Final total investment costs
5. Capital Cost (FPC) = 0.102×3304600 = 337069 INR
6. Capital Cost (ETC) = 0.102×3579100 = 365068 INR
7. Capital Cost (CPC) = 0.102×3957100 = 403624 INR
8. Capital cost (Reference) = 0.174 ×500000= 87000 INR
9. Total annual cost = Annual capital cost + Annual maintenance cost +Annual operation cost
10. Total annual cost (FPC) = 337069+44756+48386 = 430211 INR
11. Total annual cost (ETC) = 365068+47501+37775 = 450344 INR
12. Total annual cost (CPC) = 403624+51281+34149 = 489054 INR
13. Total annual cost (Reference) = 87000+7500+117916 = 212416 INR

Pay back analysis

Payback period for each option is calculated using the following equation.

$$\text{Pay back time} = \frac{\text{Final total investment cost (solar system)} - \text{Final total investment cost (Reference)}}{\text{annual operation and maintainance cost(reference system)} - \text{annual operation and maintainance cost (solar system)}} \quad (4.7)$$

In this equation, numerator shows the incremental total investment cost and denominator shows the annual operation and maintenance cost avoided (savings) with use of solar cooling options. Here the payback is calculated assuming that user will have to invest in purchasing a non-solar air conditioner if he does not want to use solar air conditioner. This method is principally similar to the regular method of finding payback period, and has been used in published studies such as Eicker et al [2014].

Payback time in the hot and dry climate with 90 m^2 flat plate collector is calculated as

$$\text{Pay back time(FPC)} = \frac{3304600 - 500000}{125416 - 93092} = 86.76 \text{ Years}$$

The Table 4.7 shows the payback time for the considered simulation cases in this study. It can be easily noticed from the table that all the payback periods are much higher than the system life, thereby meaning practically no payback period in any of the cases. The payback time is highest for the moderate climate (Bangalore) due to high investment in solar thermal cooling system for a very low cooling demand. In the warm and humid climate (Chennai) it is considerably lower as compare to others, because of the high cooling demand of the building. Evacuated tube type collector possesses a lower range of payback time than others.

Table 4.7 Payback time

FPC					
Climate (City)	70 m^2	80 m^2	90 m^2	100 m^2	110 m^2
Hot and dry (Ahmedabad)	97	89	87	86	83
Moderate(Bangalore)	213	196	191	189	190
Warm and humid (Chennai)	111	97	89	86	81
Composite (Delhi)	225	195	173	170	161
ETC					
Hot and dry (Ahmedabad)	73	76	77	80	85
Moderate(Bangalore)	141	150	155	171	190
Warm and humid (Chennai)	68	66	65*	66	70
Composite (Delhi)	132	131	135	139	146
CPC					
Hot and dry (Ahmedabad)	79	82	86	93	100
Moderate(Bangalore)	146	162	183	208	242
Warm and humid (Chennai)	73	73	78	82	91
Composite (Delhi)	131	149	159	170	184

*Lowest payback period

With the present cost structure solar thermal cooling system is not financially feasible in any climatic condition of India due to high initial cost of vapour absorption chiller, and solar collector that result in very high payback periods. In India the cost of 10 TR vapour absorption system is 3.6 times higher than the cost of vapour compression system (Packaged Air conditioner) while in other countries the vapour absorption chiller cost is only twice than the vapour compression system [Hartmann et al. 2011]. The high initial cost is also linked with high maintenance cost, where as it provides only marginal annual savings. The highest payback period is in the moderate climate due to low cooling demand of the building resulting in low utilization of system. The lowest payback period is for the warm and humid climate due to higher cooling requirement and high utilization of system on annual basis. However this type of solar thermal cooling systems may be feasible in the remote /rural area where the grid electricity is not available and people use diesel generator (DG) sets for meeting cooling requirements such as preservation of life savings drugs, air conditioning of medical rooms in emergency areas etc.

The payback time for the solar thermal cooling system is higher than the life of the system hence the internal rate of return (IRR) is not calculated.

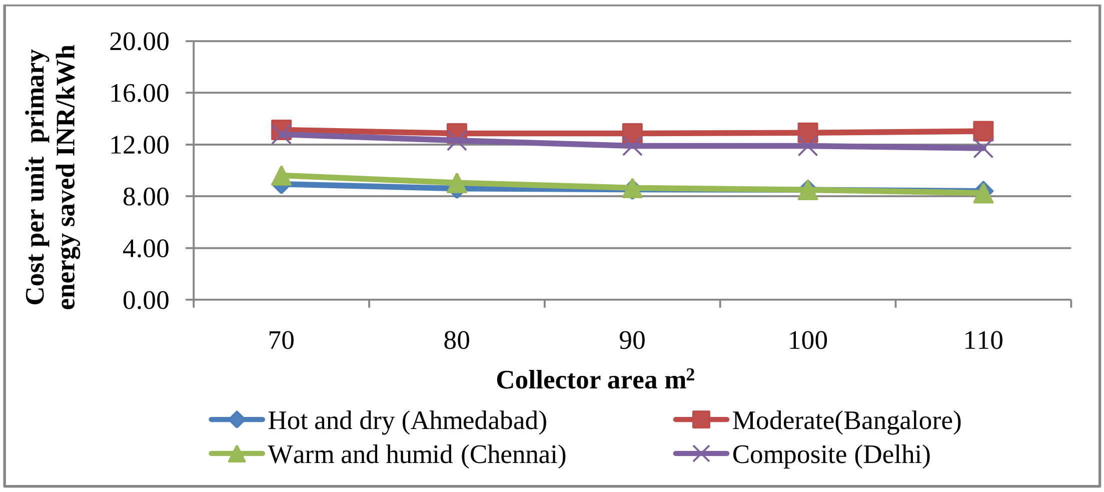
4.5.4 Cost per unit primary energy saved

Cost of saved primary energy is calculated using the following equation.

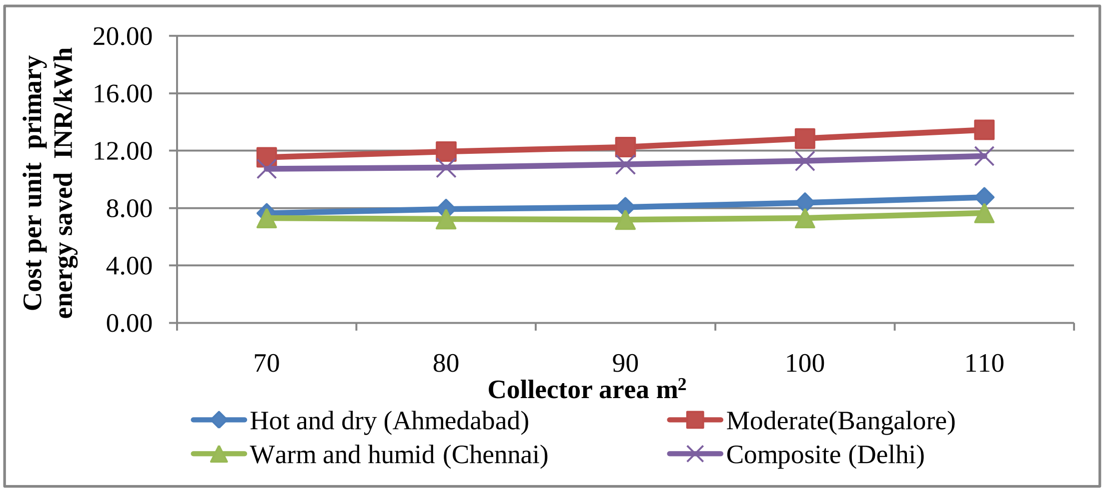
$$Cost\ per\ unit\ \ primary\ energy\ saved\ \ = \frac{\text{annual extra cost of solar system}}{\text{annual primary energy savings}} \qquad (4.8)$$

Fig 4.23 shows the cost per unit primary energy saved with the collector area and type. It has been observed that the cost of saved energy is highest for the moderate climate (Bangalore) having the lowest cooling demand and as the cooling demand is increased the cost of saved primary energy decreases. This result has good agreement with the work of Hartmamm et al. 2011. For warm and humid climate (Chennai) and hot and dry climate (Ahmadabad) due to higher solar fraction achieved by the solar thermal cooling system the annual extra cost of solar system is utilized in higher savings of primary energy resulting in the lower cost per unit primary energy saved. From fig 4.23 a shows that in the case of FPC the cost of saved primary energy decreases with the collector area and it is lesser in the moderate climate (Bangalore) and we observe highest decreasing rate in the warm and humid climate (Chennai). The drop in the cost per unit primary energy saved is high when collector area is increased from 70-90 m^2 but we notice a moderate drop when we further increase the collector area.

Fig 4.23 b shows that the cost per unit primary energy saved is increasing slowly with the collector area because in the evacuated tube type of collector the solar fraction is high even at the lower collector areas and an optimum collector area exist at which the cost per unit primary energy saved is lowest in all the climates. Fig 4.23 c show the cost per unit primary energy saved for the CPC and this indicates that the cost increases as the collector area increases. When we increase the collector area the annual extra cost of solar system also increases but the annual savings do not increase in that ratio resulting in higher cost per unit primary energy saved.



(a)



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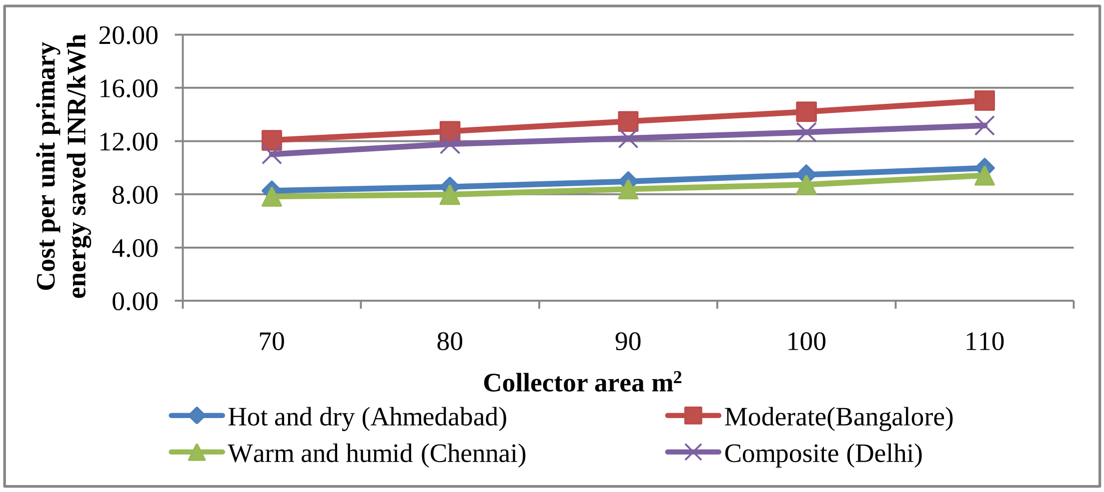


(c)

Fig 4.23 Cost per unit primary energy saved (a) FPC (b) ETC(c) CPC

The cost per unit primary energy saved is calculated as (Hot and dry climate-90 m^2 FPC)

1. Annual extra cost of solar = Total annual cost (solar) - Total annual cost (reference)

1a. Annual extra cost of solar = 430212 - 212416 = 217795 INR

2. Cost of saved primary energy = annual extra cost of solar/ saved primary energy

2a. Cost of saved primary energy = 217795/ 25581= 8.51 INR/ kWh_{PE}

4.6 Sensitivity Analysis

With the present cost structure in India the solar thermal cooling system is not feasible in any climate due to higher investment cost. In coming future as the investment cost becomes low and the cost of electrical energy based on fossils fuels increases then this cooling system may be feasible. To see the effect of investment cost on payback period sensitivity analysis is carried out on the following parameter.

	Parameter	Range
1	Total investment cost sensitivity analysis	-50% to +50%
2	Electricity cost sensitivity analysis	-50% to +50%

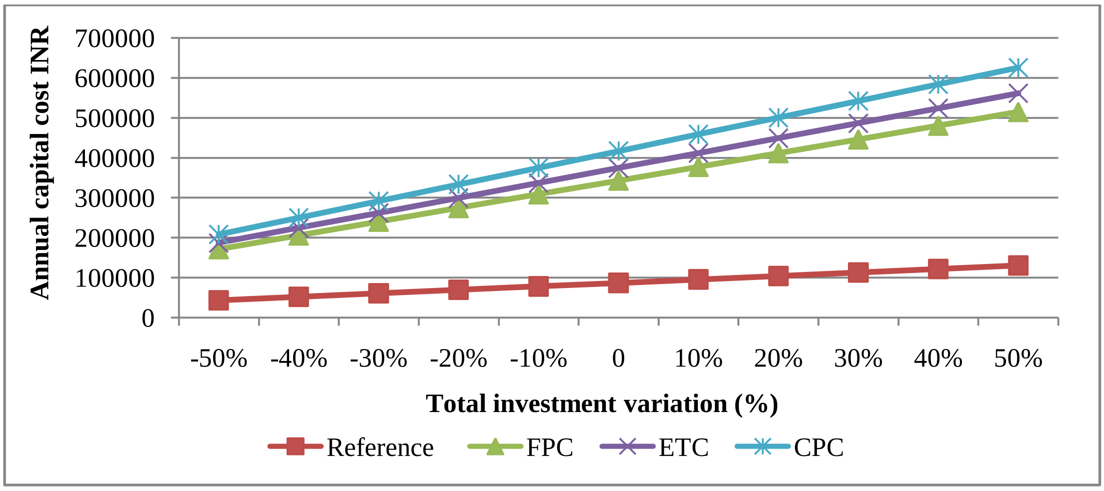
4.6.1 Total investment cost sensitivity analysis:

Sensitivity analysis is carried out for total investment cost variation in the range of ± 50%. It has been assumed that cost of solar air conditioner may reduce due to two possibilities:-

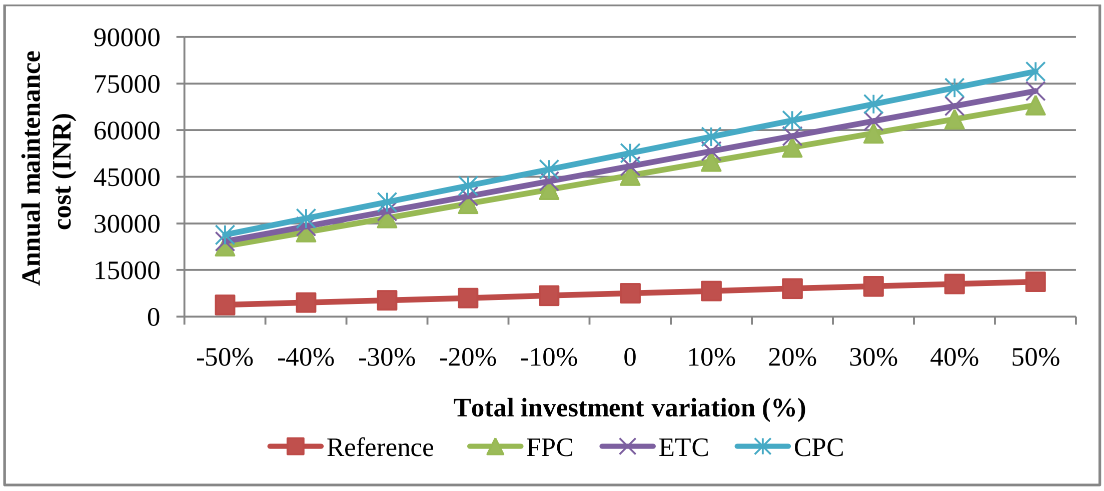
(a) Economy of scale

(b) Subsidy given by Government

The scenario of reduction of system cost up to 50% has been analyzed and results are presented in the thesis. These may be considered to be covering the scenario of Government subsidy at different levels i.e 10%,20%,30%,40%,50% of the system cost.The highest cooling demand is in the warm and humid climate and results in the lower payback periods. So here sensitivity analysis is carried for the warm and humid climate with 90 m^2 collector area.



(a)



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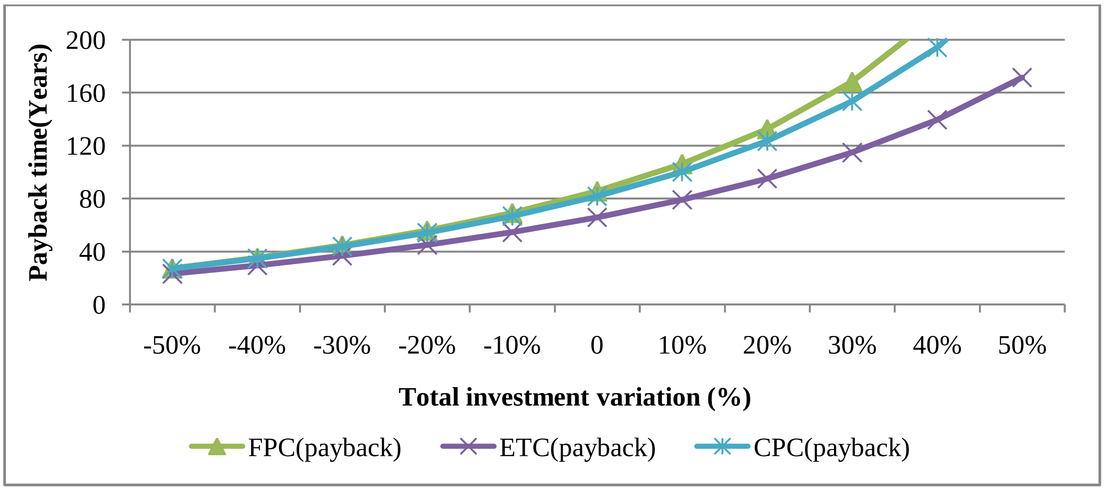


(b)

Fig 4.24 Influence of total investment cost variation on (a) Annual capital cost (b) Annual maintenance cost (c) Payback time (Collector area -90 m^2, warm and humid climate)

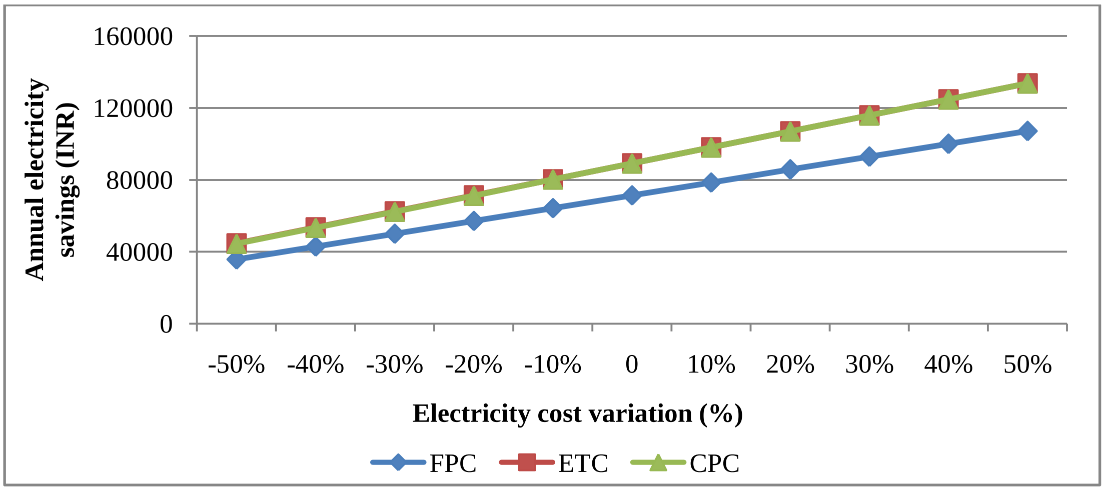
Fig.4.24 (a)-(c) show the variation of annual capital cost, annual maintenance cost and payback periods for the FPC, ETC and CPC type collectors. The packaged air conditioner powered by grid power is assumed as the reference system cost. Fig 4.24 a shows that as the total investment cost decreases the difference between the annual capital cost of the solar thermal and reference system also reduces consequently the annual maintenance costs also reduces. It leads to lower payback periods.

It is observed from the fig.5.16 c that as the cost of total investment is decreased by 50 % the payback period also decreases and comes down to 28 year for FPC, 23 years for ETC and 26 years for CPC . At present costs in India the payback periods is 89 years, 65 years and 78 years for FPC,ETC, and CPC respectively for the same considered case in the warm and humid climate. However a considerable amount of payback time lowers when the investment cost fell by 50% but still it is not justifiable because of the high initial investment.

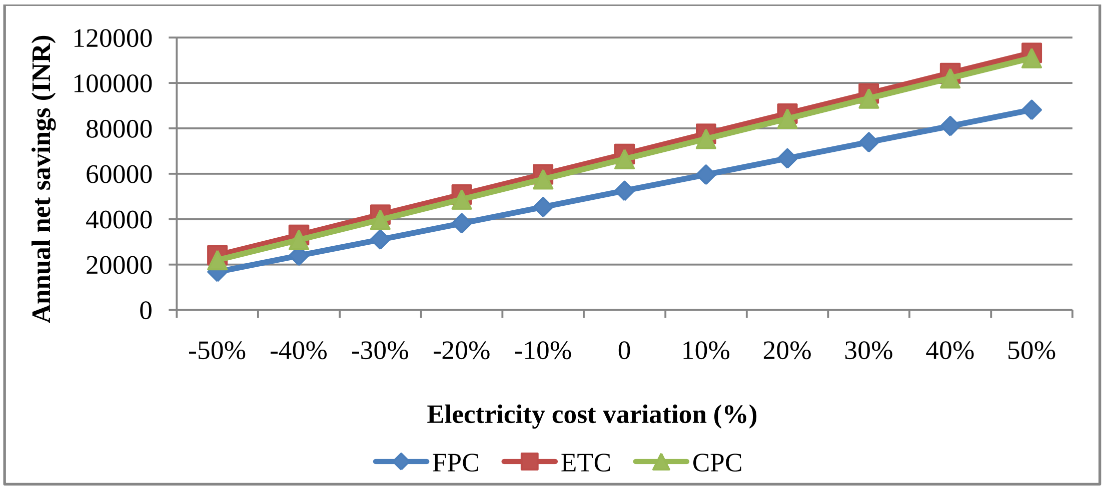
4.6.2 Electricity cost sensitivity analysis

From the last two decades the cost of solar energy equipments has fallen down significantly as the production of these units is increasing, at the same time the cost of electricity is also increasing continuously. In India major part of electricity is generated by power plants using fossils fuel. The hike in the price of fossil fuels leads to continuous hike in the electricity cost. In this condition the solar thermal cooling system may become viable in future.

The effect of change in electricity cost on payback time after consideration the 50 % reduction in the investment cost is carried out. Fig 4.25 (a) (b) and (c) show the effect of electricity cost on annual electricity savings, annual net savings and payback time respectively. It has been observed from the fig.4.25 a, b and c that as the electricity cost increases the annual electricity savings, annual net savings also increase thus the payback time decreases. In future, if the electricity prices are increased by 50 % then the payback will come down to 17, 14, 16 years for the FPC, ETC and CPC respectively.



(a)



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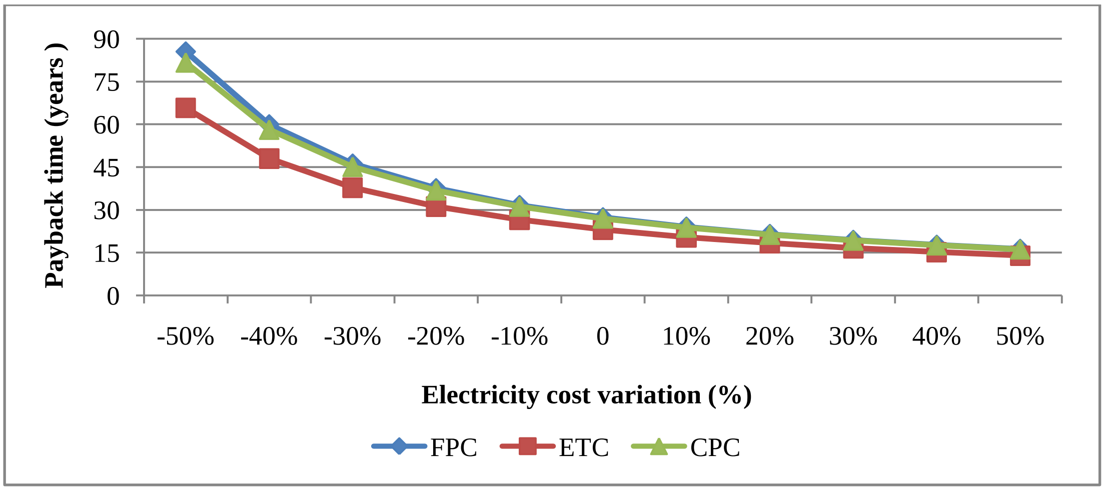


(c)

Fig 4.25 Influence of electricity cost variation (a) Annual electricity savings (b) Annual net savings (c) Payback time

4.7 Summary of Chapter

It can be conclude from the performance analysis of the solar thermal cooling system that it is technically feasible because it offers good solar fraction in the range of 0.51-0.94 in the considered climates and collector areas. The primary energy savings reaches up to 74%. Financially with the present cost structure, solar thermal cooling system is not feasible in any climatic condition of India due to high initial cost of vapour absorption chiller, and solar collector. The high initial cost is also linked with high maintenance cost, where as it provides only marginal annual savings that result in very high payback periods (65-242 years). The highest payback period is in the moderate climate due to the low cooling demand of the building resulting into low utilization of system. Lowest payback period is for the warm and humid climate due to larger amount of cooling requirement and high utilization of system on annual basis.

Sensitivity analysis shows that in coming future the as the total investment cost decreases and electricity prices increases, the payback period came down. If the total investment fall down to its 50% and electric prices are hike 30% than the payback period came down within the system life.

CHAPTER 5 PERFORMANCE ANALYSIS OF SOLAR PHOTOVOLTAIC COOLING SYSTEM

In this chapter the modeling and performance analysis of solar photovoltaic cooling system described in chapter 3 sub sections 3.5 is presented and discussed. The analysis of solar photovoltaic cooling system is carried out in two scenarios i.e. grid supported and net metering provision. Solar photovoltaic cooling system with battery storage is not analysed because initial analysis shows that the capital cost of storage system is very high and it is also linked with annual maintenance cost. System also requires reoccurring cost at every 4-5 year for replacement of batteries. In the net metering provision it is assumed that the electricity purchase and selling price are same.

5.1 Modeling of Solar Photovoltaic Cooling System

The solar photovoltaic cooling system consists of photovoltaic panel, inverter and a packaged terminal air conditioner. The capacity of packaged terminal air conditioner is decided based on the peak cooling load of the building. In this study the cooling load of the 225 m^2 square building was calculated by the TRNSYS simulation program. According to peak cooling demand a 10TR cooling capacity packaged air conditioning model FVPGR13NY1 is selected for the entire office building in the hot and dry, warm and humid and composite climate. The total power consumption of packaged air conditioner is 14.9 kW [Daikin catalogue]. The air conditioner is powered by the array of photovoltaic panels. For moderate climate 24.5 kW (7TR) capacity air conditioner is taken. The same area of photovoltaic panel has been varied in the range 70-110 m^2 with an interval of 10 m^2 similar to the collector area taken in the solar thermal cooling system.

Another important component of the solar photovoltaic cooling system is inverter. It converts the DC power to AC and sends it to the load and utility. In this study a simple inverter model is used that have only two inputs, Input power and Load power and it calculates three outputs, Power in, Power out and Excess power

(Power to or from utility (>0 if purchased, <0 if sell-back)). If the power demanded by the air conditioner is less than generated by the photovoltaic panel then the remaining power is taken from the public grid (Grid supported system). If the power generated by the photovoltaic panel is greater than the power consumed by the air conditioner than the surplus power is fed to the public grid only in case of availability of net metering scheme. The regulator and inverter efficiency is taken as 0.97 [55].

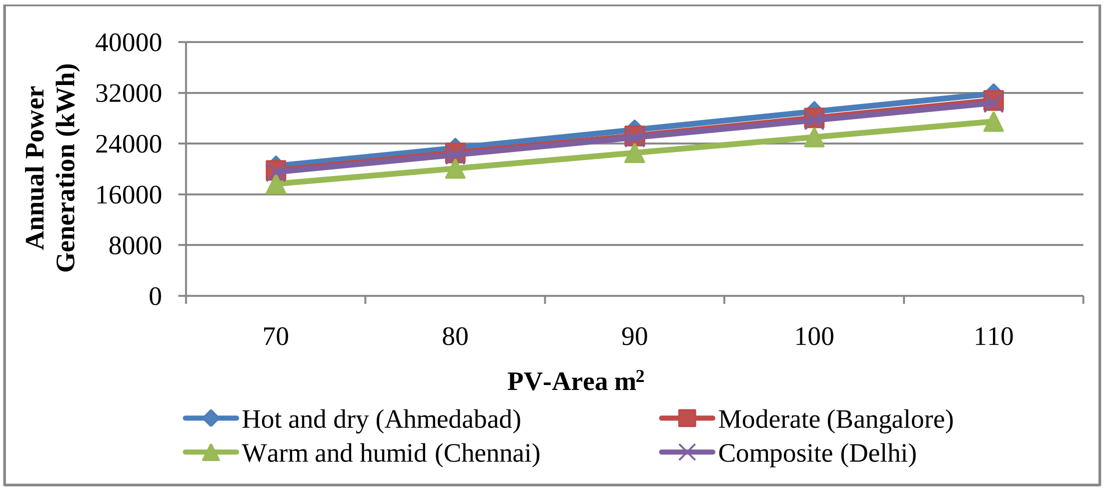
5.2 Performance Analysis of Photovoltaic Panel

In this section the annual power generation and capacity utilization factor are presented and discuseed.

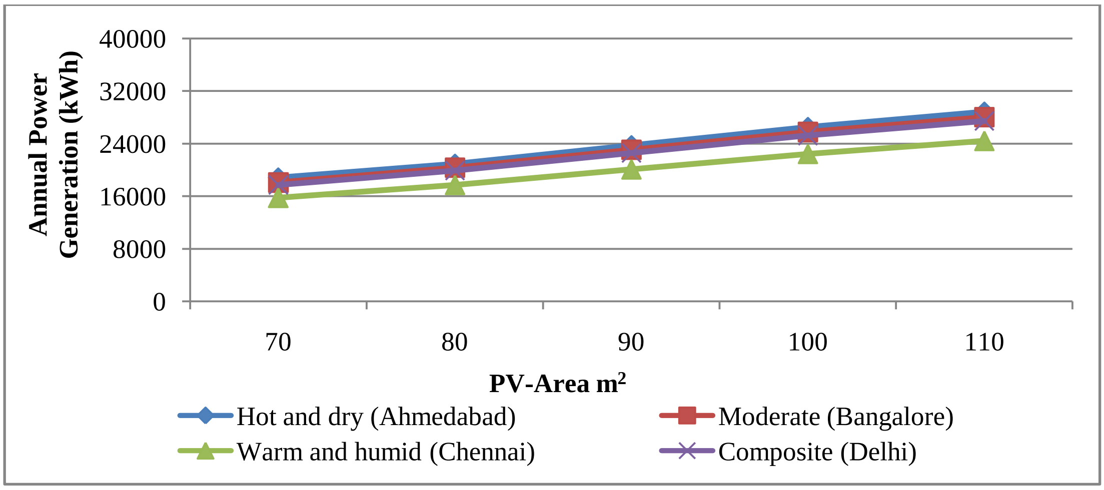
5.2.1 Annual Power Generation

Fig 5.1 (a), (b) and (c) show the annual power generation of the mono-crystalline, poly- crystalline and thin- film cells respectively. It has been observed from the fig.5.1 that the annual power generation is directly proportional to the PV area in all types of PV cells and climates. In the hot and dry climate (Ahmedabad) the annual power generation is highest due to the highest availability of solar radiation and for warm and humid climate (Chennai) it is lowest because of the lowest solar radiation. In the moderate (Bangalore) and composite climate (Delhi) the annual power generation ranges between the hot and dry (Ahemdabad) and warm and humid (Chennai).

The annual power generation is highest for the mono crystalline and lowest for the thin film cells because of their efficiency. The annual power generation for the poly crystalline cells lies between mono and thin film. The same trend is observed in all the climates. In the mono crystalline cells the annual power generation is 26180, 25204, 22561 and 24963 kWh for the hot and dry (Ahmedabad) , moderate (Bangalore), warm and humid (Chennai) and composite climate (Delhi) respectively when 90 m^2 PV area is used. It is 23755, 23070, 20088 and 22589 kWh respectively when the poly crystalline cells and 19932, 18488, 16706 and 18620 kWh for thin film cells are used with the same area of 90 m^2.



(a)



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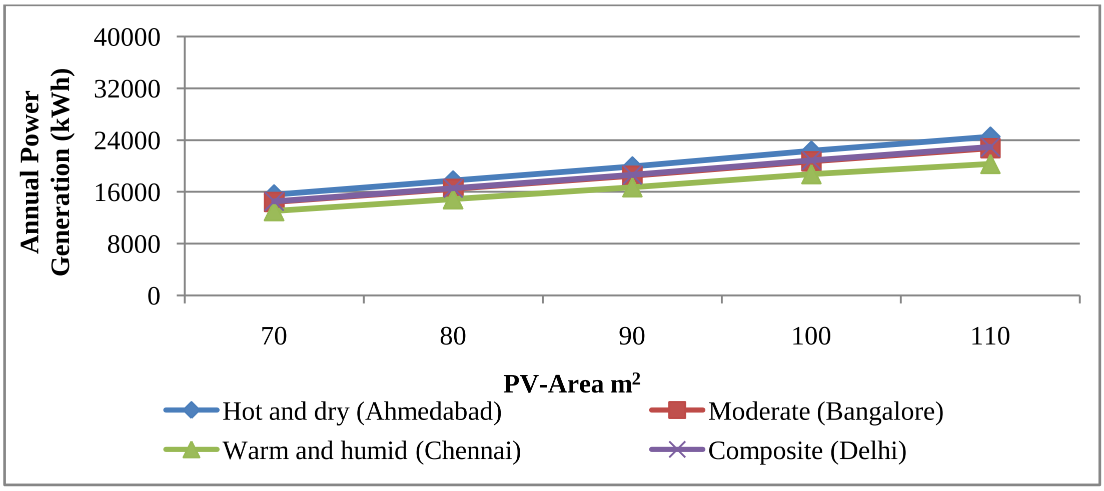


(c)

Fig.5.1 Annual power generation with PV area (a) Mono (b) Poly (c) Thin-film

5.2.2 Capacity Utilization Factor (CUF)

The capacity utilization factor (CUF) is defined as the ratio of the annual energy output (E_{AC}) of the PV system to the amount of energy the PV system would generate if operated at full rated power (P_{PV}) for 24 hr per day for year and is given by

$$\text{Capacity Utilisation Factor (CUF)} = \frac{\text{Actual annual energy output } (E_{AC})}{\text{Rated PV power } \times 8760} \quad (5.1)$$

Fig.5.2 shows the capacity utilization factor for the three types of cells in the considered climates. It has been observed from the fig. 5.2 that the CUF is highest for the hot and dry climate (Ahmedabad) and lowest for the warm and humid climate (Chennai) like the annual power generation because of the highest solar radiation in hot and dry climate (Ahmedabad) and lowest in warm and humid climate (Chennai) Thin film cells have the highest CUF due to least loss of power generation efficiency at elevated temperature and it also captures the energy throughout the day even at lower radiation. At elevated temperature the power generation of crystalline cells decreases so in hot and dry climate the difference of CUF between crystalline and thin film is higher than others.

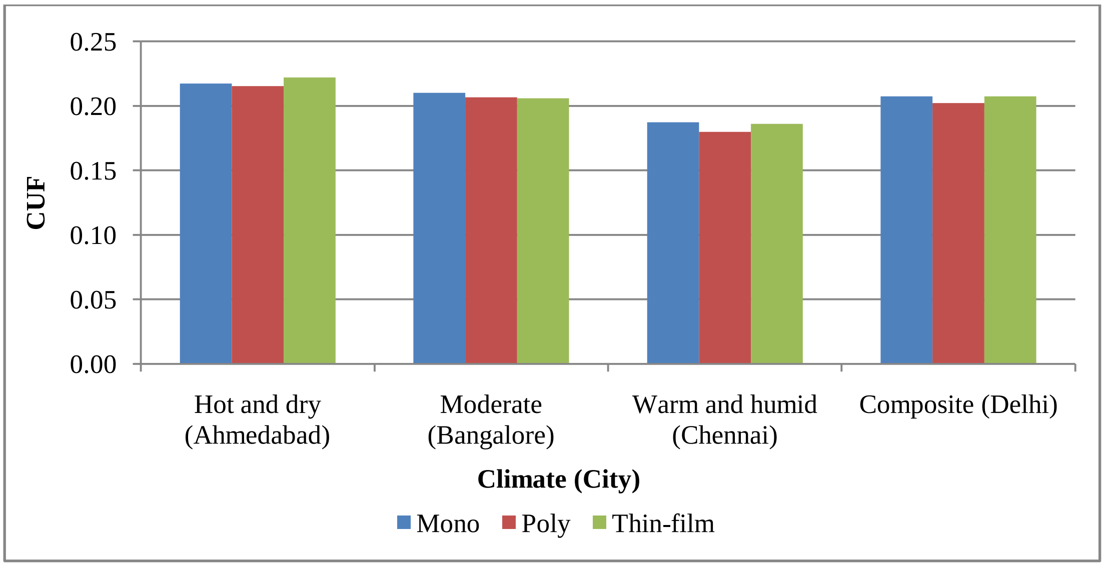


Fig.5.2 CUF for Mono, Poly and Thin-film in considered climates

5.3 Performance Analysis of System

In this section solar fraction and electrical (Grid) COP describing the performance of solar photovoltaic cooling system are presented and discussed.

5.3.1 Solar Fraction

Grid supported solar photovoltaic cooling system

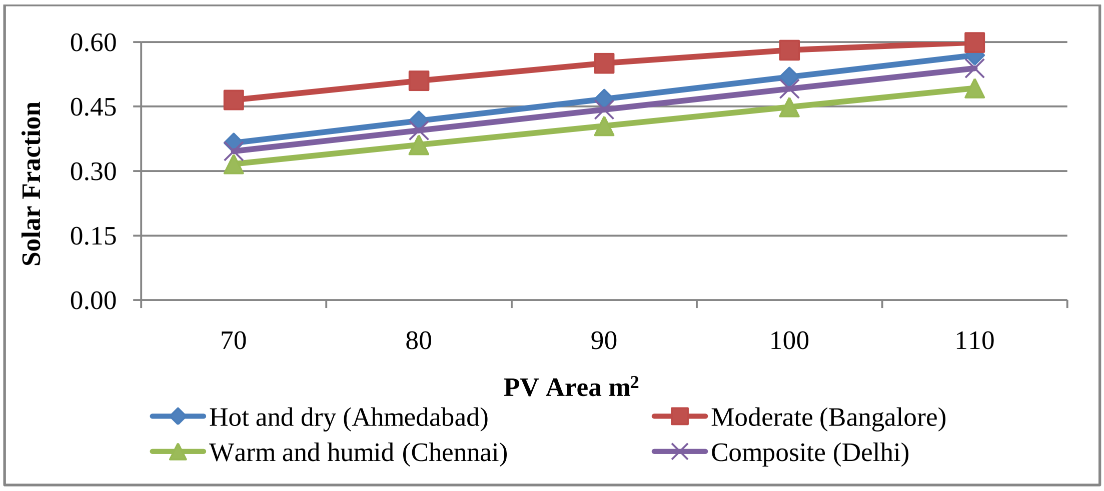
It is the ratio of the annual cooling produced by the solar to the total annual cooling demand of the building. In case of solar photovoltaic cooling system it is defined as the ratio of annual energy contributed by solar photovoltaic panel to the total input energy required by air conditioner.

$$\text{Solar Fraction(Grid supported)} = \frac{\text{Annual energy contributed to air conditioner directly by PV}}{\text{Total input energy required by air conditioner}} \qquad (5.2)$$

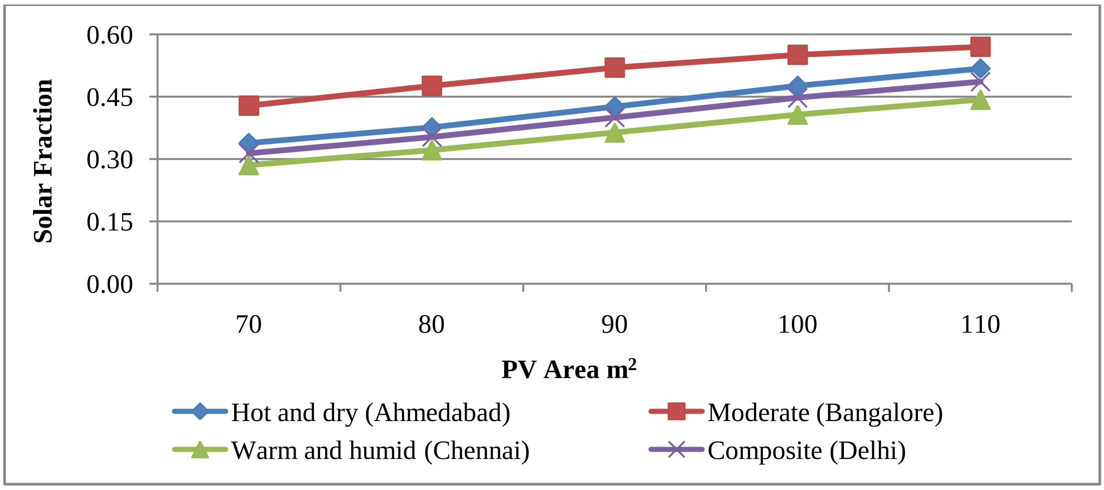
Fig 5.3 (i) (a), (b) and (c) show the variation of annual solar fraction with the photovoltaic area for the three types of panel Mono, Poly and Thin film respectively. It is clear from the fig 5.3 (a), (b) and (c) that as the area of photovoltaic panel is increased the annual solar fraction also increases for all type of panels and climate. The annual power generation directly depends on the area of PV panel so any increase in the PV area increases the power generation and more power directly supplied to the cooling system enhances the solar fraction.

The highest solar fraction (0.47-0.60) for mono-cells is observed for the moderate climate due to lowest cooling demand 131 kWh_{th}/m^2 and moderate power generation (CUF 21%). The lowest solar fraction (0.32-0.49) for mono-cells is observed in the warm and humid climate due to very high cooling load 225 kWh_{th}/m^2 and high annual power consumption of 17912 kWh_{el}.

For hot and dry and composite climate the annual solar fraction ranges between 0.37-0.57, and 0.35-0.54 respectively. The value of solar fraction for the hot and dry and composite climate is also higher because of the good matching between the power generation and the cooling demand in the summer months.



(a)



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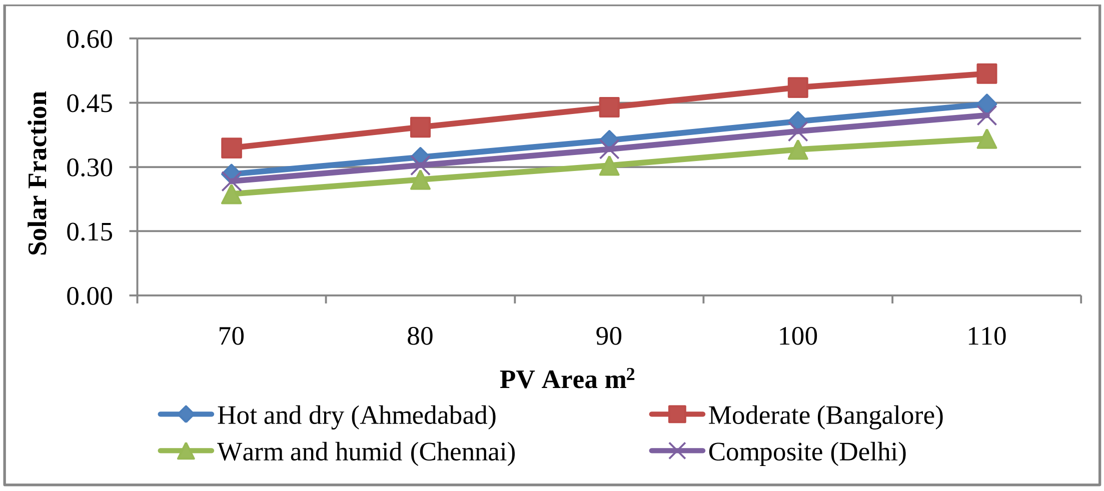


(c)

Fig.5.3 (i) Annual solar fraction with PV area (a) Mono (b) Poly (c) Thin-film

The annual solar fraction is lower for the thin film cells because of the low efficiency of cells for all type of climates. The annual power generation for the poly cell is higher than the thin film but lower than the mono-cell so the annual solar fraction for poly-cell lies between the mono and thin film cells.

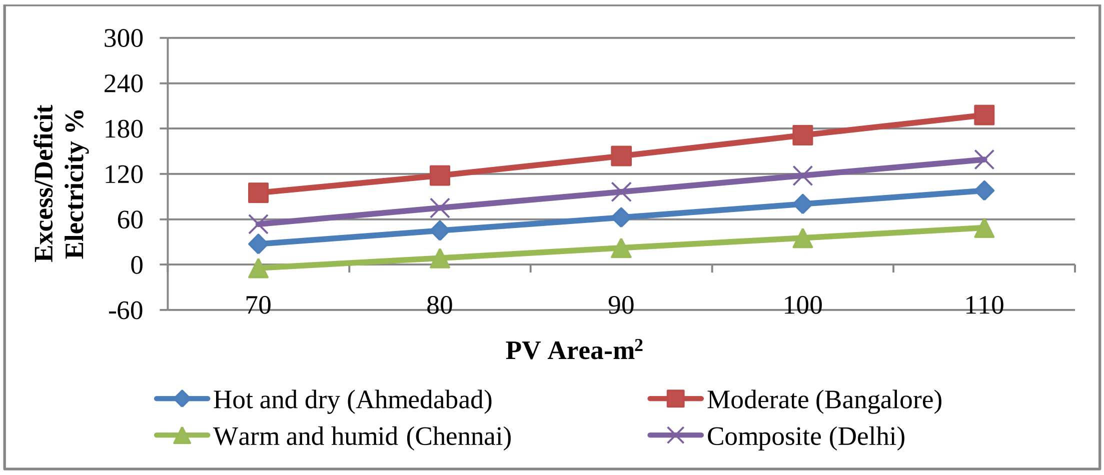
Net metering solar photovoltaic cooling system

The excess/deficit electricity for the net metering photovoltaic cooling system may be defined as the

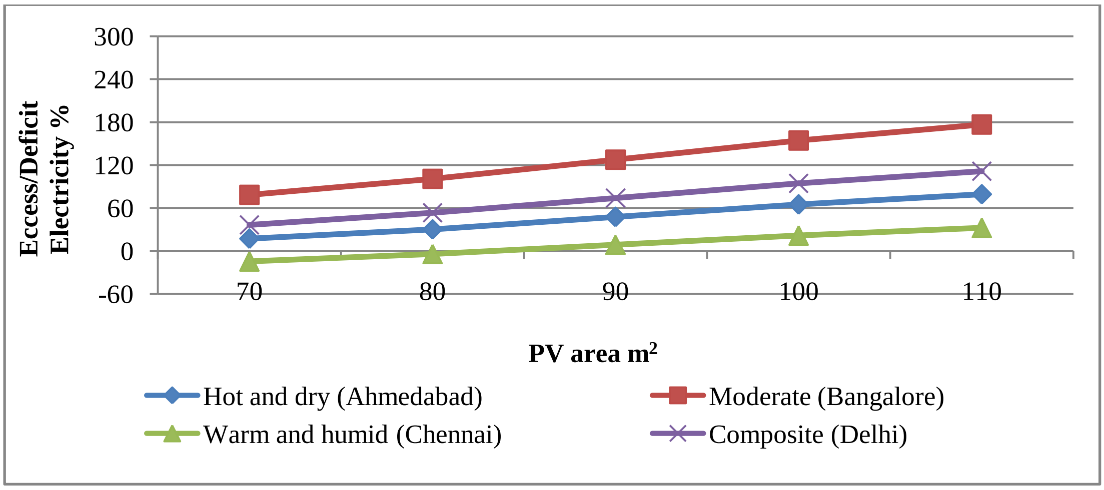
$$\frac{\text{Excess}}{\text{Deficit}}\text{Electrictiy \%} = \frac{\text{Useful annual power generation by PV} - \text{Total input energy required by the air conditioner}}{\text{Total input energy required by air conditioner}} \tag{5.3}$$

Fig 5.3(ii) a, b, c shows the excess/deficit electricity for mono, poly and thin film cells respectively in the net metering system. It has been observed from the fig 5.3(ii) that the annual excess electricity is highest for the mono cells and lowest for the thin film cells because of the cell efficiency. The positive value indicated that the useful annual power generation by the PV is higher than the annual power consumption of the air conditioner and difference between them is called excess electricity and if it is less than zero or negative value it is called deficit electricity.

The annual excess electricity percentage is highest in the moderate climate because in this climate the cooling energy demand of the building is low resulting in low power consumption (9825kWh$_{el}$) by air conditioner while the annual power generation is moderate. In the warm and humid climate the annual cooling energy demand is highest (51220 kWh$_{th}$) and power consumption of air conditioner (17912 kWh$_{el}$) is also highest but the annual power generation is lowest (21884 kWh-90m^2-mono) resulting in the deficit electricity. Excess PV electricity may be used to grid export and if deficit in any case it may be import from the grid.



(a)



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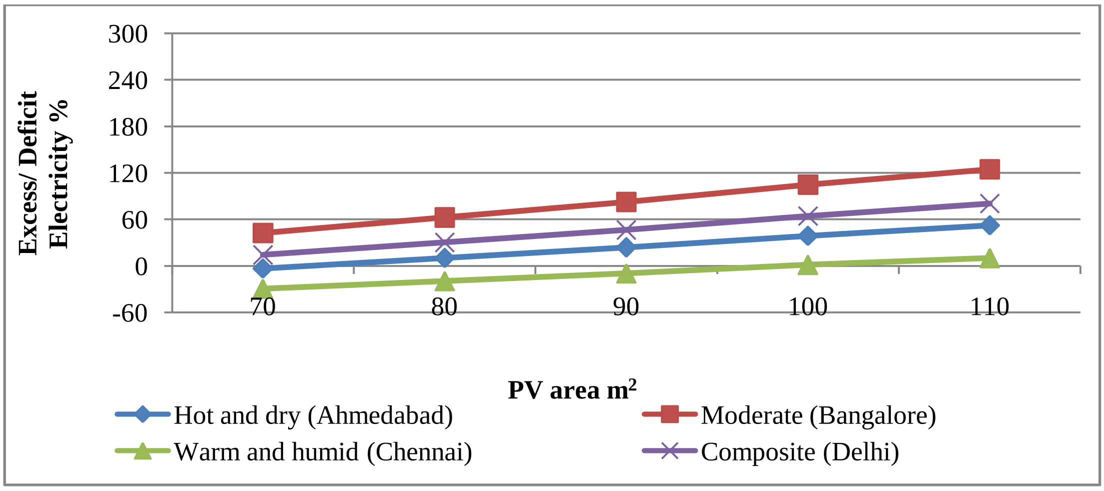


(c)

Fig.5.3(ii) Annual Excess/Deficit Electricity % (net metering) with PV area (a) Mono (b) Poly (c) Thin-film

5.3.2 Electrical (Grid) COP of system

The Electrical (Grid) COP of the system is defined as the annual cooling demand of the building divided by the annual electricity consumption from the grid. Fig.5.4 (a), (b), and (c) show the Electrical (Grid) COP of the system. It has been observed from the fig.5.4 that as the PV area increases the electrical (Grid) COP also increases because at higher PV area the power generation is also higher and the consumption of grid electricity is lesser resulting in the higher electrical COP. The COP of the packaged air conditioner is ranging between 2 to 3 in the considered climates but here electrical (Grid) COP is ranging between the 4 and 7.6. The increase in COP is due to the electricity generation by the PV.

The value of electrical (Grid) COP is highest in the moderate climate (Bangalore) and lowest in the warm and humid climate (Chennai) in all type of PV panels. The value of electrical(Grid) COP for hot and dry and composite climates range between the moderate and warm and humid climates. In the moderate climate the cooling demand of the building is low so it requires low power consumption and amount of power generated by PV is moderate so only a small amount of power is required from the grid which results in high Electrical (Grid) COP. In the warm and humid climate (Chennai) the cooling demand of the building is quite high and at the same time the annual power generation by the PV is relatively lower therefore balance of electrical power that is taken from grid is higher as compared to other climates resulting in low electrical (Grid) COP.

The annual power generation from the mono crystalline cells is highest among all types of cells in all locations. The cooling demand and electrical power consumption is same for all types of cells which result in lowest electrical power consumption from the grid in mono cells, hence highest electrical (Grid) COP. In the thin film cells power generation is least so air conditioner system requires highest electrical power from grid resulting in lowest electrical (Grid) COP.

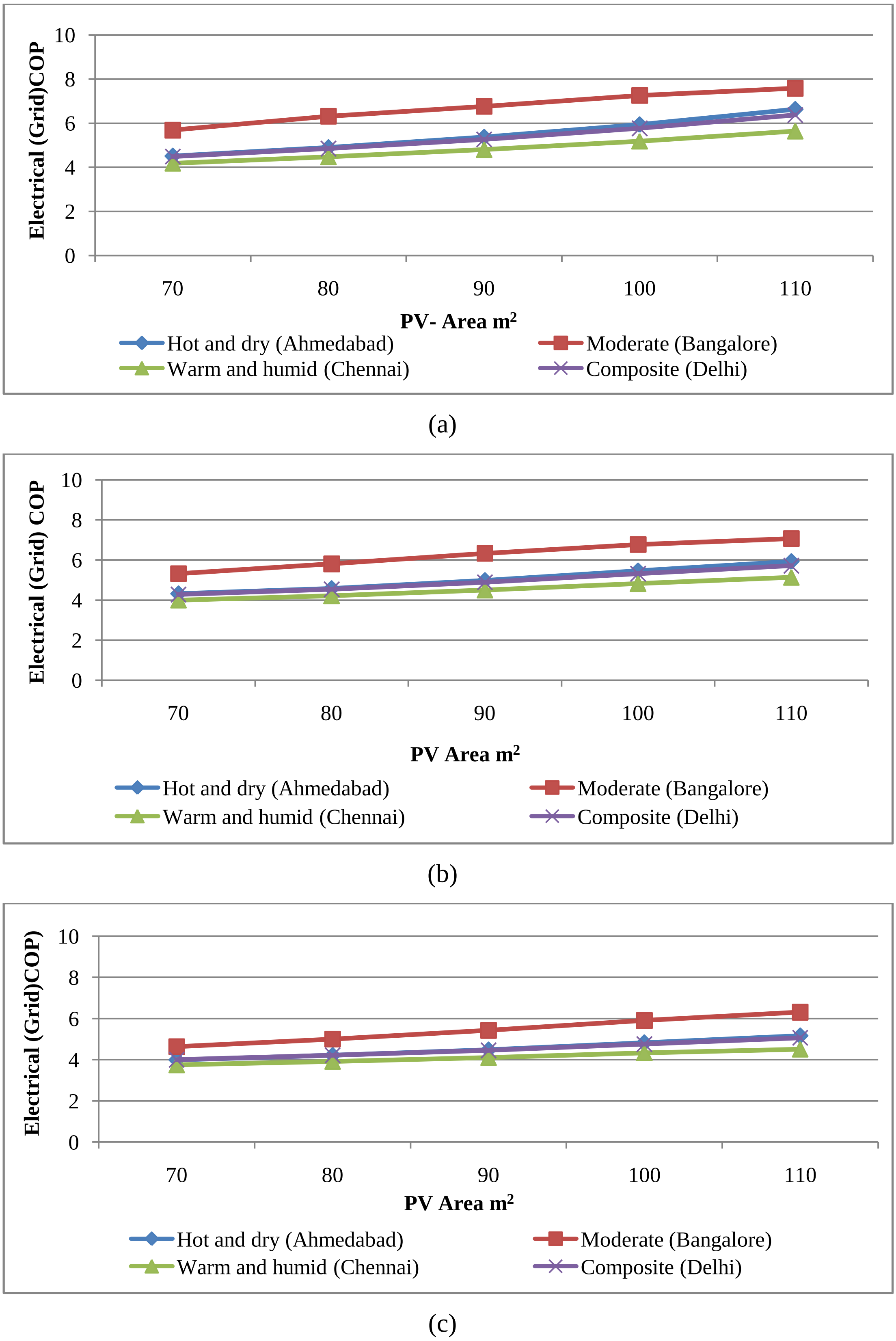


Fig.5.4 Electrical (Grid) COP with PV area (a) Mono (b) Poly (c) Thin-film

5.4 Energy and Economic Analysis

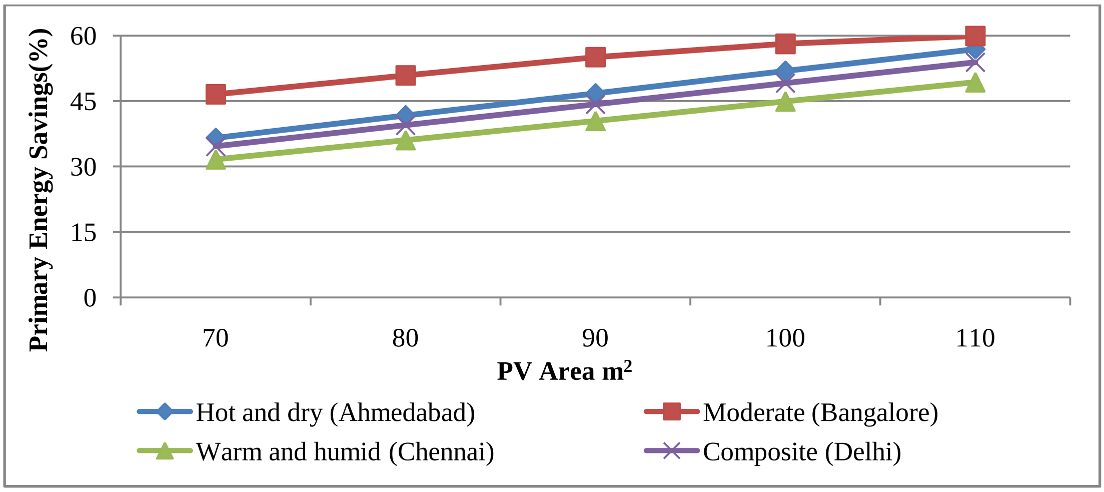
In this section primary energy savings, specific primary energy savings, payback period and cost per unit of primary energy saved are presented and discussed related to energy and economic performance of solar photovoltaic cooling system.

5.4.1 Primary energy savings

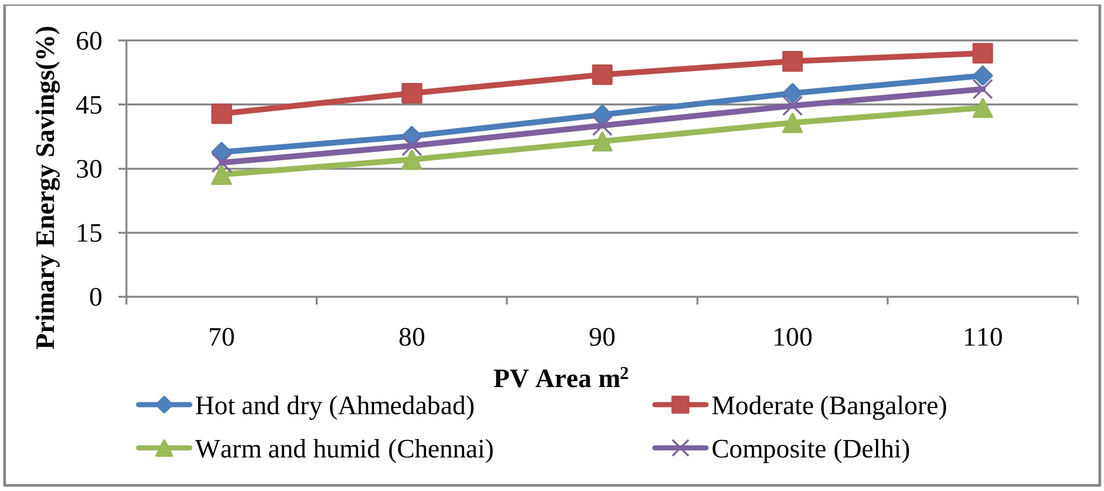
Fig.5.5 a-c shows the primary energy savings (grid supported) for the mono, poly and thin film cell respectively. It is clear from the fig.5.5 that the primary energy savings increase with the PV area for all the climates and type of PV panels. The highest primary energy saving are for the mono cell and lowest for the thin film cells, and for poly cells it is between mono and thin film.

The primary energy savings are highest 46%-60% for the moderate climate and lowest for the warm and humid climate, the reason is same as in the annual solar fraction. The cooling demand is very high for the warm and humid climates and power generation is lesser resulting in the low primary energy savings i.e 31%-49%. The range of primary energy savings in the hot and dry climate and composite climate are 37-57% and 34-54 % respectively in the monocrysttalline based system.

In the net metering provision the primary energy savings is corresponding to the annual solar fraction. In a case when annual solar fraction is equal to 1, it indicates that the power generated by the PV is equivalent to the power consumption of air conditioner. In that case power purchase from the grid is equivalent to the power sold to grid resulting net balance is zero. This is corresponding to 100% primary energy savings. If the value of solar fraction is greater than 1 it is corresponding to more than 100% primary energy saving. Fig.5.3 (ii) shows the annual excess/deficit electricity percentage (net metering) with PV area for Mono, Poly and Thin-film respectively. Fig. 5.3(ii) shows that the PV area at which annual excess/deficit electricity percentage is zero that is the minimum PV area required to provide the cooling if net metering is adopted. So in this way excess electricity is highest in the moderate climate because of the lowest cooling laod and it is deficit or very less excess in the warm and humid climate, due to cooling highest demand.



(a)



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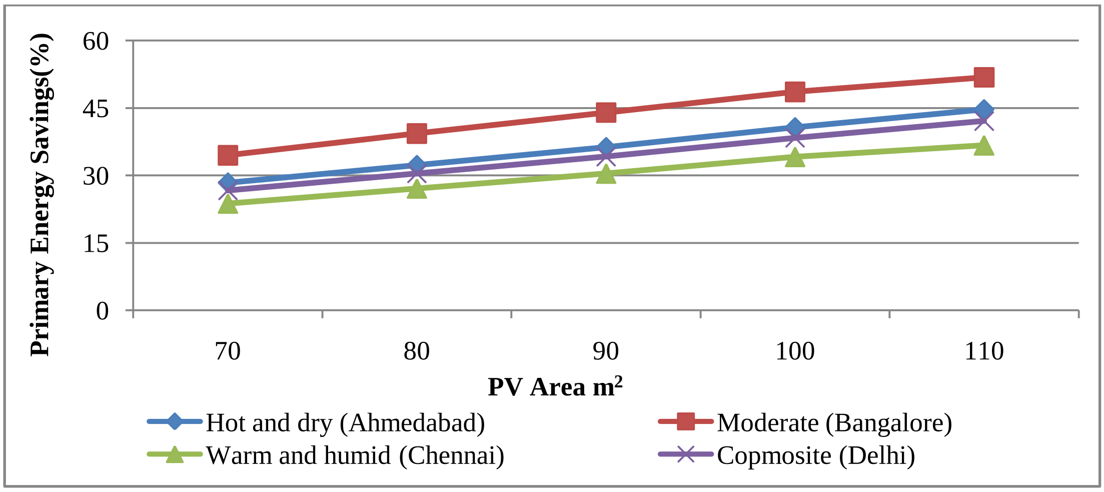


(c)

Fig. 5.5 Primary energy savings with PV area (a) Mono (b) Poly (c) Thin-film

5.4.2 Specific primary energy savings

Specific primary energy savings are defined as the primary energy saving per m^2 of PV area. It has been observed from the fig.5.6 that specific primary energy savings are highest for the mono crystalline cells and lowest for the thin film cells in all the considered climates. The specific primary energy savings for polycrystalline cells are between mono and thin film cells.

The highest specific primary energy saving for the hot and dry climate are 225, 206 and 175 kWh_{PE}/m^2 for the mono, poly and thin film respectively. Lowest specific primary energy savings for the moderate climate (Bangalore) are 168,152 and 129 kWh_{PE}/m^2 for mono, poly and thin film respectively. In the warm and humid climate (Chennai) the cooling demand of the building is very high hence better utilization of PV generation resulting in higher specific primary energy savings i.e. 224, 201, and 168 kWh_{PE}/m^2 for the mono, poly and thin film respectively. In the composite climate the specific primary energy savings are 169,152, and 130 kWh_{PE}/m^2 for the mono, poly and thin film cells respectively.

The specific primary energy savings are constant with the PV area because as the PV area increases the annual power generation increases proportionally and primary energy savings also.

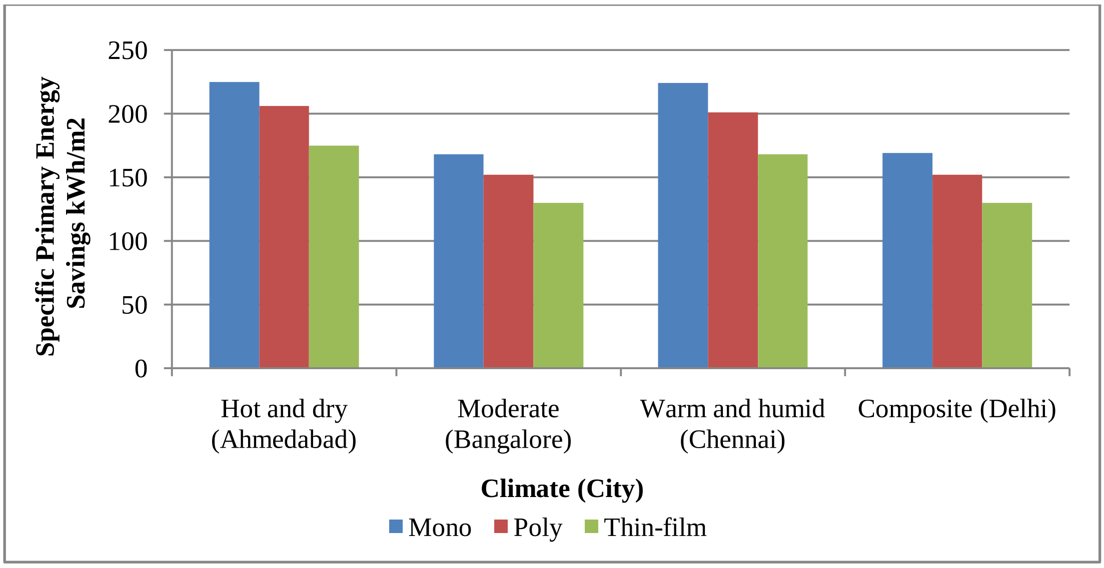


Fig.5.6 Specific primary energy savings for Mono, Poly and Thin-film

5.4.3 Economic analysis

In the last chapter we have carried out economic analysis for the solar thermal cooling system with reference to a packaged air conditioner operated by the grid power. In this chapter the economic analysis is carried out for the solar photovoltaic cooling system. Similarly to solar thermal, the cost of energy economics is divided into three categories: Capital cost, maintenance cost and operational cost. Table 5.1 shows the cost of the components associated with the solar photovoltaic cooling and reference system.

Table 5.1 Cost and parameters considered in the calculation

S.No.	Component	Size	Unit	Cost	Source
1	Photovoltaic Panel – Mono crystalline	70- 110 m^2	Rs/W	42	CERC New Delhi 2014
2	Photovoltaic Panel – Poly crystalline	70- 110 m^2	Rs/W	40	
3	Photovoltaic Panel – Thin film	70- 110 m^2	Rs/W	36	CERC New Delhi 2014
3a	Module cost		Percentage of total project cost	55%	CERC New Delhi 2014
4	Civil and General works ,		Percentage of total project cost	8%	CERC New Delhi 2014
5	Mountings Structure			7%	CERC New Delhi 2014
6	Power Conditioning Unit			8%	CERC New Delhi 2014
7	Life of Solar Panel		Years	25	CERC New Delhi 2014
8	Discount Rate		8%		State Bank of India
9	Inflation Rate		7%		www.inflation.eu
10	Electricity Escalation Rate		5%		CERC
11	Degradation Rate		0.5%		K Branker et al. 2011
12	Electricity Sell and Purchase from Grid		Rs/kWh	7.55	CEA New Delhi 2013
13	Annuity Factor – Solar			0.09	Calculated in sec 5.4.3 page 174
14	Annuity Factor – Non solar			0.17	

Capital Cost

The capital cost includes the cost of photovoltaic panel, civil and general works, mountings structures, power conditioning units and packaged air conditioner. Fig 5.7 shows that the capital cost of three types of PV panels varying with area and for reference case for the all climates except moderate (Bangalore). It has been observed from the fig.5.7 that the capital cost of the mono-crystalline cell is highest and thin film cell is lowest. In the reference system only the cost of packaged air conditioner is considered. The capital cost of reference case (non solar) is same in the hot and dry, warm and humid and composite climate while it is different for moderate climate and is 3.5Lac.

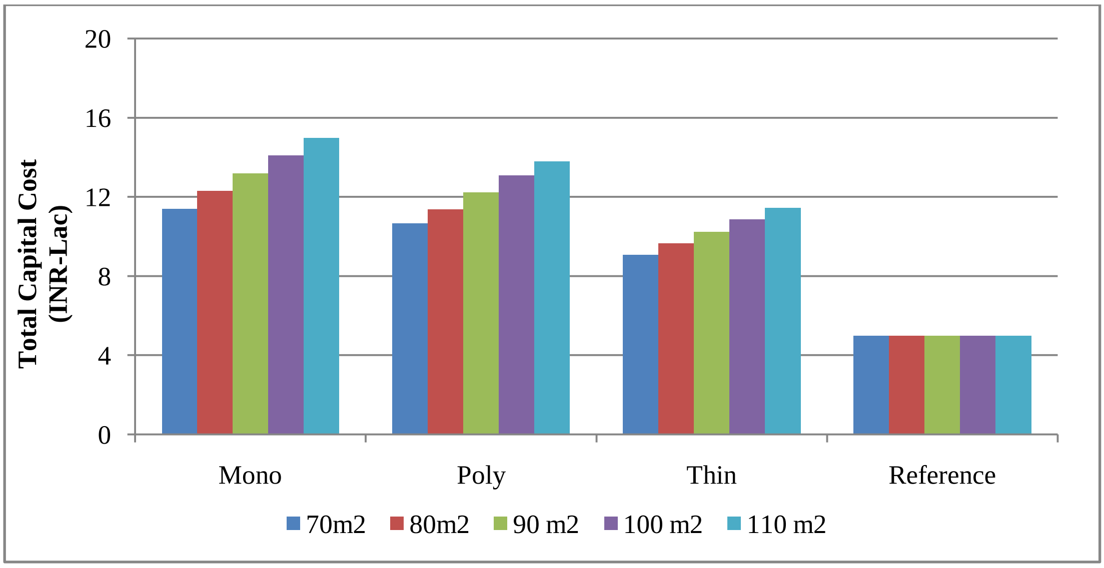


Fig.5.7 Capital costs with PV area

The following parts show the calculation of the investment cost of the system having the PV area of 90 m^2.

1. Solar photovoltaic panel (Mono) = 42 Rs/W × 13750 W = 577500 INR
2. Solar photovoltaic panel (Poly) = 40 Rs/W × 12750 W = 510000 INR
3. Solar photovoltaic panel (Thin) = 36 Rs/W × 10250 W = 369000 INR
4. Project cost (Mono) = 577500*100/55 = 1050000 INR
5. Civil, General, Mounting, Structure and Power Conditioning Unit cost = 23% of project cost.

5a. Mono = 23 % of 1050000 = 241500 INR

6. Packaged air conditioner cost = 500000 INR
7. Total investment cost (Mono) = (Solar PV cost + Civil and General cost + Mounting and Structure cost + Power conditioning Unit cost + Air Conditioning cost)

7a. Total investment cost (Mono) = 577500+241500+500000= 1319100 INR

7b. Total investment cost (Mono-moderate climate) = 577500+241500+350000= 1169000 INR

Annual maintenance cost

This cost is considered as the annual expenses on the maintenance during a year in routine. The maintenance cost is considered as 1% for solar and 1.5 % for non solar components [Tscotous 2010]. Fig 5.8 shows the annual maintenance cost for the solar photovoltaic cooling system and for reference. The cost of maintenance is linked with the capital cost so it is same for all climates except moderate and varies with the type of PV panel and area. In the moderate climate the size of absorption chiller is different so the capital cost and maintenance cost is also different than other climates and it is lowest.

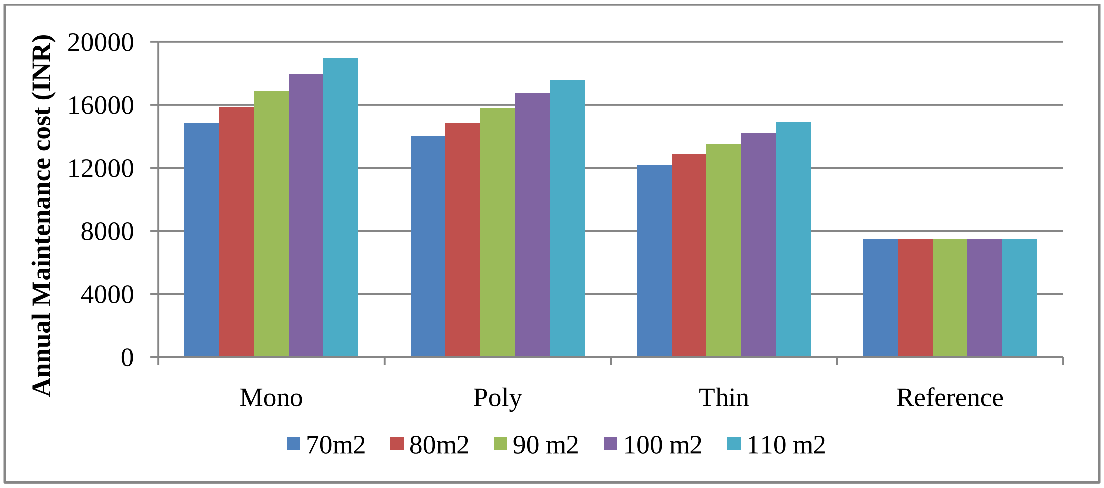


Fig.5.8 Annual Maintenance Cost with PV Area

The calculation for the maintenance cost of the system having the PV area of 90 m^2 is as follows:

1) Maintenance cost = 1% × (Investment on solar component) + 1.5 % × (Investment cost of other components)
2) Maintenance cost (Mono) = 1% ×[577500] + 1.5% ×[1319100-577500]= 5775+11124= 16899 INR
3) Maintenance cost (Mono-Moderate climate) = 1% ×[577500] + 1.5% ×[1169100-577500]= 5775+8872= 14648 INR
4) Maintenance cost (Reference) = 1.5% ×[500000] = 7500 INR
5) Maintenance cost (Reference-moderate climate) = 1.5% ×[350000] = 5250 INR

Annual operational cost

Table 5.2 shows the operational cost for the solar photovoltaic cooling system and reference system. This cost is calculated by the cost of electricity per kWh multiplied by the annual consumption of electricity. As the PV area increases the operation cost decreases due to low electricity consumption from the grid. In the warm and humid climate the cooling demand of the building is high so annual electricity consumption is also high resulting in high operational cost. In the reference the operational cost is the cost of electricity consumption by the packaged air conditioner. The calculation for the operational cost of the system having the PV area of 90 m^2 for hot and dry climate is as follows:

1. Operational cost = Electricity consumption × Cost of electricity INR/kWh
2. Operational cost (Mono) = 8313kWh × 7.55 INR/kWh = 62760 INR
3. Operational cost (Reference) = 15619 kWh ×7.55 INR/kWh=117916

Table 5.2 Operational cost

Mono						
Climate	**70 m^2**	**80 m^2**	**90 m^2**	**100 m^2**	**110 m^2**	**Reference**
Hot and Dry (Ahmedabad)	74795	68778	62760	56743	50794	117916
Moderate (Bangalore)	39913	35915	33552	31264	29931	74179
Warm and Humid (Chennai)	92439	86466	80493	74521	68549	135236
Composite (Delhi)	60863	56364	51866	47370	42918	93099
Poly						
Hot and Dry (Ahmedabad)	77953	73546	67629	61712	56815	117916
Moderate (Bangalore)	42642	39072	35814	33495	32077	74179
Warm and Humid (Chennai)	96592	91761	85963	80166	75335	135236
Composite (Delhi)	63856	60200	55813	51428	47803	93099
Thin film						
Hot and Dry (Ahmedabad)	84530	79834	75139	69921	65226	117916
Moderate (Bangalore)	48930	45320	41819	38401	35967	74179
Warm and Humid (Chennai)	103162	98651	94139	89127	85673	135236
Composite (Delhi)	68282	64791	61301	57423	53932	93099

Total annual cost

The total annual cost includes the fraction of capital cost converted by the annuity method, annual maintenance cost and annual electricity consumption cost (operational cost). Table 5.3 shows the total annual cost in the considered climates and PV area. It is clear that the total annual cost increases with the PV area in all the climates and it is highest for the mono cells. In the reference system total annual cost is constant irrespective of collector type and area but it varies with the climate. The total annual cost is highest for the warm and humid climate (Chennai) and lowest for the moderate climate (Bangalore) due to highest and lowest cooling demand respectively.

Table 5.3 Total annual cost

Mono						
	70	80	90	100	110	Reference
Hot and dry (Ahmedabad)	236633	240011	243388	246766	250212	212416
Moderate (Bangalore)	173399	178795	185828	192934	200996	140332
Warm and humid (Chennai)	254276	257699	261121	264544	267966	229736
Composite (Delhi)	222701	227597	232493	237393	242336	187599
Poly						
Hot and dry (Ahmedabad)	232111	235160	238191	241221	243781	212416
Moderate (Bangalore)	168447	172334	178024	184652	190691	140332
Warm and humid (Chennai)	250750	253375	256525	259675	262300	229736
Composite (Delhi)	218014	221814	226375	230937	234769	187599
Thin film						
Hot and dry (Ahmedabad)	221986	223330	224674	226167	227511	212416
Moderate (Bangalore)	158033	160463	163002	166294	169900	140332
Warm and humid (Chennai)	240618	242146	243674	245372	247958	229736
Composite (Delhi)	205737	208287	210836	213668	216217	187599

The sample calculation for the annual cost of the system having the mono crystalline panel for 90 m^2 in the hot and dry climate is given below.

1. Annuity factor $= \frac{i \times [(1+i)^n]}{[(1+i)^n - 1)]}$ (5.4)

   Where i = interest rate, n = lifetime of the system or component

2. $\text{Annuity factor (solar photovoltaic system)} = \frac{0.08 \times [(1+0.08)^{25}]}{[(1+0.08)^{25} - 1)]} = 9.4$

3. $\text{Annuity factor (reference system)} = \frac{0.08 \times [(1+0.08)^{8}]}{[(1+0.08)^{8} - 1)]} = 17.4$

4. Annual capital cost = annuity factor × Final total investment costs

5. Annual capital Cost (Mono) = 0.094×819000 + 0.174×500000 = 76722+87007 = 163730 INR

6. Annual capital cost (Reference) = 0.174 ×500000= 87007 INR

7. Total annual cost = Annual capital cost + Annual maintenance cost +Annual operation cost

8. Total annual cost (Mono) = 163730+16899+62760 =243388 INR

9. Total annual cost (Reference) = 87000+7500+117916 = 212416 INR

Payback time- grid supported system

The payback time for the solar photovoltaic cooling system is calculated using the following equation.

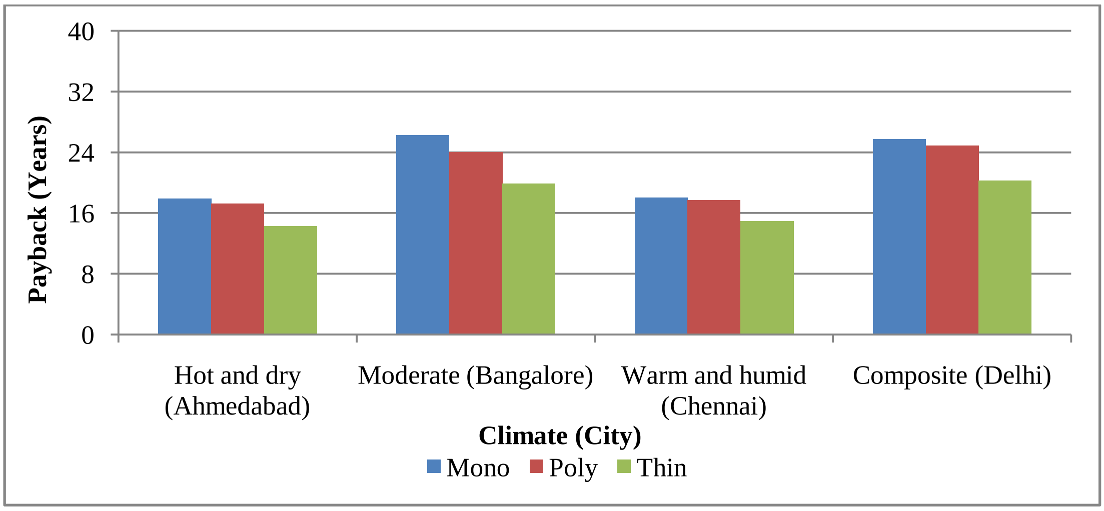
$$\text{Pay back time} = \frac{\text{Final total investment cost (solar system)} - \text{Final total investment cost (Reference)}}{\text{annual operation and maintainance cost(reference system)} - \text{annual operation and maintainance cost (solar system)}} \quad (5.5)$$

The sample calculation for the hot and dry climate (Ahemdabad) with 90 m^2 PV area.

$$\text{Pay back time (Mono)} = \frac{1319100 - 500000)}{125416 - 79658}$$

$$\text{Pay back time (Mono)} = 17.90 \text{ years}$$

Fig 5.9 (a) show the payback time for the mono, poly and thin film in the considered climates. Fig 5.9 (a) shows the payback periods if power generated by PV panels is used only in cooling is considered. If it is less than required by the air conditioner than the power is taken from grid but if the power generated is more than the required by the air conditioner then this excess amount is dumped. It has been observed from the fig.5.9a that the payback periods are highest for the moderate climate (Bangalore) and lowest for the hot and dry climate (Ahmedabad). The payback periods are lowest for the thin film cells than the mono and poly because of the lowest investment cost and highest power generation for the same capacity.



5.9 (a) Payback time (Grid supported)

Payback time- net metering system

The payback time for the solar photovoltaic cooling system with net metering is calculated using the following equation.

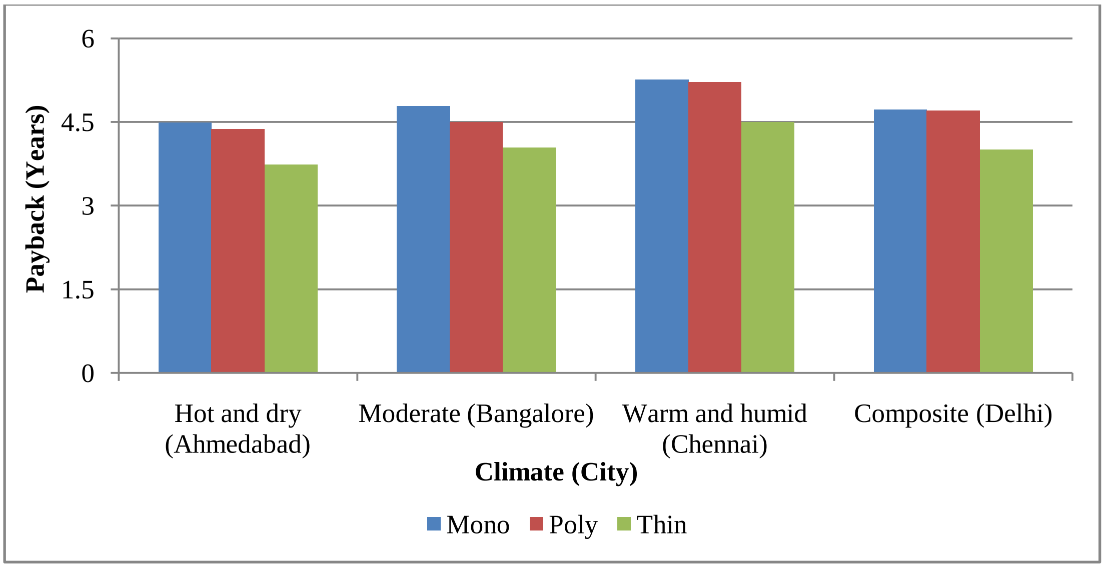
$$\text{Pay back time} = \frac{\text{Final total investment cost (solar system)} - \text{Final total investment cost (Reference)}}{\text{cost of power generated by PV} - \text{maintenance cost of PV}} \quad (5.6)$$

The sample calculation for the hot and dry climate (Ahemdabad) with 90 m^2 PV area.

$$\text{Pay back time (Mono)} = \frac{1319100 - 500000)}{191725 - 16898}$$

$$\text{Pay back time (Mono)} = 4.49 \text{ years}$$

Fig 5.9 (b) shows the payback time for the net metering options. In this option when power generation is less than required by the air conditioner then the remaining power is purchased from the grid and if the power generation by PV is greater than required by the air conditioner then the surplus power is sell out to public grid. The cost of electricity purchase and sell out is assumed to be same. It has been observed from the fig.5.9b that the lowest payback period is for the hot and dry climate (Ahmedabad) because of the highest annual power generation. The highest payback periods are for the warm and humid climate (Chennai) having the least power generation. Thin film cells perform better than the crystalline cells so have the least payback period in all the considered climates.



5.9 (b) Payback Time (Net metering)

Internal rate of return (IRR)

In the payback time calculation the discount rate and life of component is not considered. In order to see the effect of discount rate and life of component the internal rate of return calculation is carried out. In this calculation discount rate 8%, inflation rate 7% and electricity escalation rate 5% are taken. Fig 5.10 shows the internal rate of return for the mono, poly and thin film cell in the considered climates with the net metering options. It has been observed from the fig.5.10 that the IRR is highest for the hot and dry climate (Ahmedabad) and lowest for the warm and humid climate (Chennai).

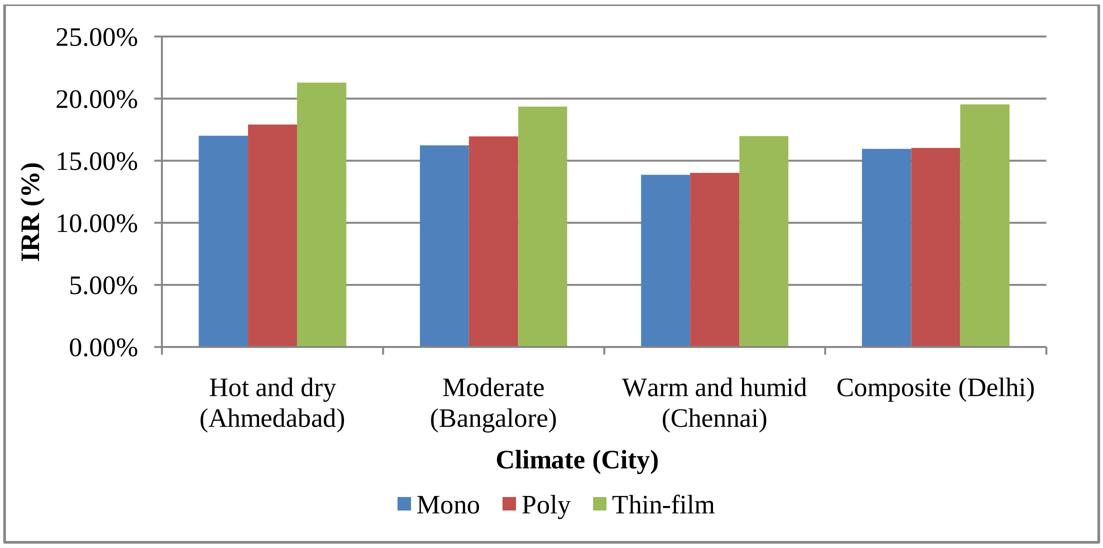


Fig. 5.10 Internal rate of return (IRR) - Net metering

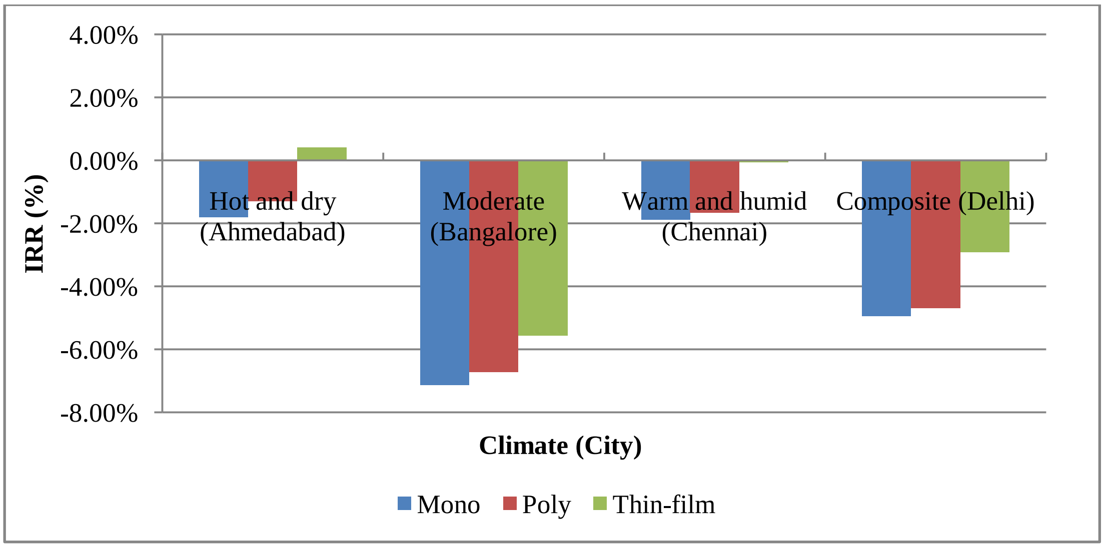


Fig. 5.11 Internal rate of return (IRR) – Grid supported

The IRR for the hot and dry climate is 17.01, 17.90 and 21.29 % for the mono, poly and thin film respectively. The lowest IRR for the warm and humid (Chennai) is 13.86, 14.02 and 16.98% for the mono, poly and thin film respectively. The value of IRR is greater than the discount rate in all the considered cases and climates so from the economic point of view this system is feasible.

Fig 5.11 shows the internal rate of return for the grid supported solar photovoltaic cooling system. It is clear from the fig.5.11 that the IRR is negative for all the climates and types of cells except in thin film cells in hot and dry climate. The negative value of IRR shows that solar photovoltaic cooling system (grid supported) is not feasible for only cooling purpose. In hot and dry climate the IRR is better than the other climates. Thin film cells have better performance than the mono and poly.

5.4.4 Cost per unit primary energy saved

Fig 5.12 show the cost per unit primary energy saved for the mono, poly and thin film cells in the considered climates. It is an indicator which shows that how much amount is required for saving of 1 kWh_{PE} of primary energy. It has been observed from the fig.5.12 that the value of cost per unit primary energy saved is lowest for the hot and dry climate (Ahmedabad) because of the good cooling demand and good radiation resulting in higher utilization of solar energy. In the composite climate (Delhi) the cost of primary energy saved is highest because of the lowest cooling demand resulting in lower primary energy savings by the same investment. For moderate climate the cost of primary energy saved is also higher because of the lowest annual cooling demand.

Thin film cells performs better than the other cells and has the lowest capital cost resulting in the lowest cost per unit primary energy saved. The same trend is observed in all the considered climates.

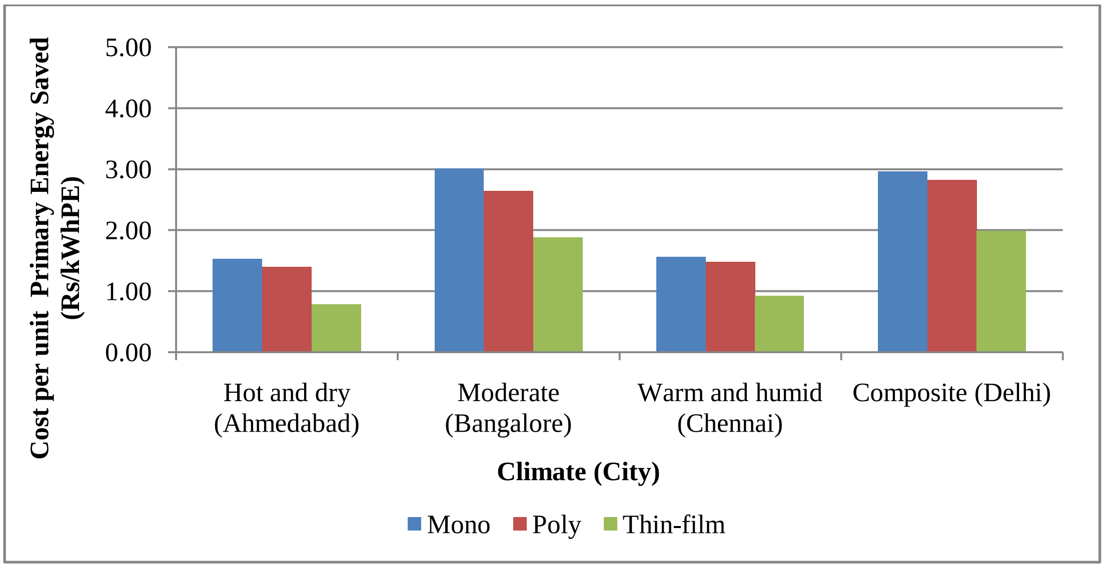


Fig.5.12 Cost per unit primary energy saved for Mono, Poly and Thin-film

5.5 Sensitivity Analysis

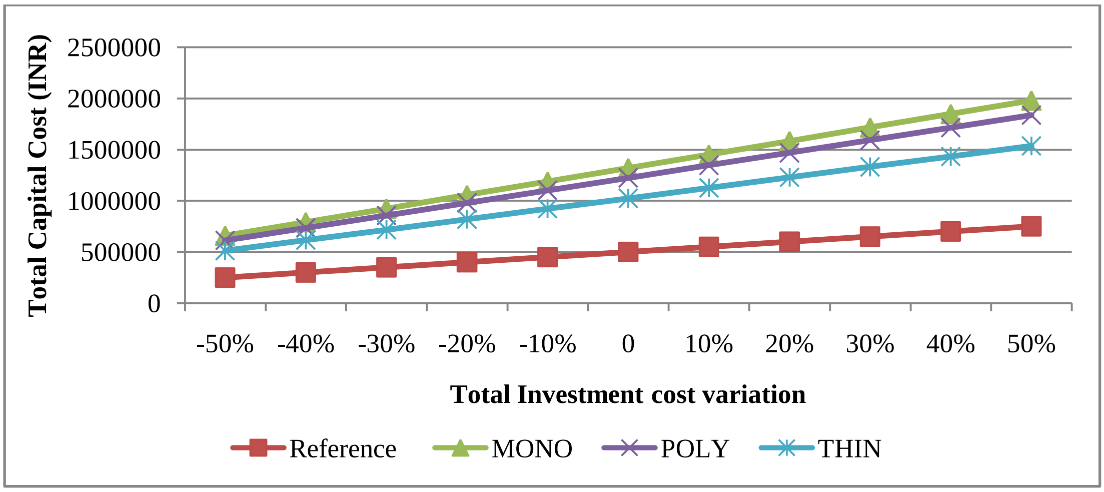
With the present cost structure in India the solar photovoltaic cooling system (grid supported) is not feasible in any climate for only cooling applications. It has payback periods in the range of 14-35 years. However it is feasible with the net metering option having the lower payback period in the range of 4-6 years. In coming future as the investment cost becomes low and the cost of electrical energy based on fossils fuels increases then this cooling system may be feasible. To see the effect of investment cost on payback period sensitivity analysis is presented with respect to following parameters.

	Parameter	**Range**
1	Total investment cost sensitivity analysis	-50% to +50%
2	Electricity cost sensitivity analysis	-50% to +50%

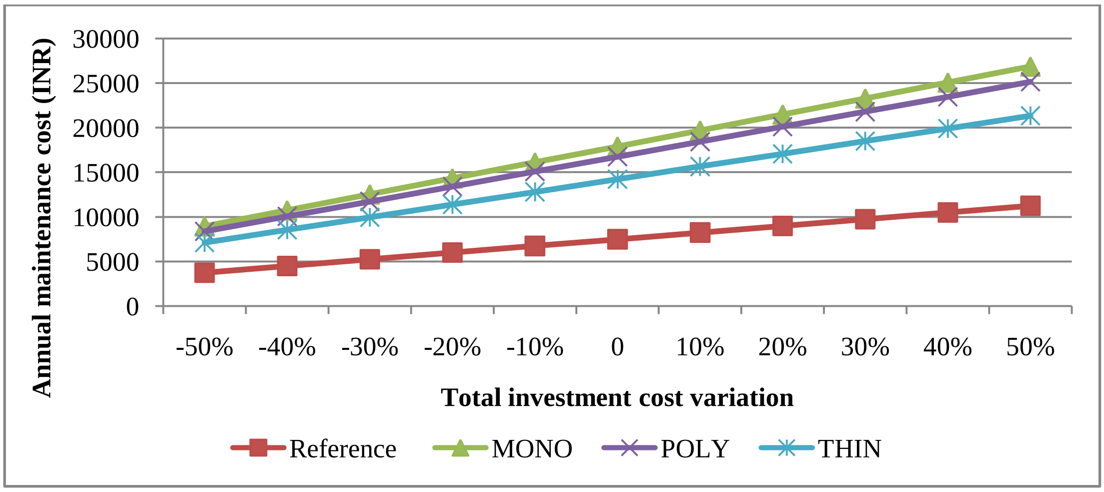
5.5.1 Total investment cost sensitivity analysis:

The highest cooling demand is in the warm and humid climate that results in the lower payback periods. So here sensitivity analysis is carried for the warm and humid climate with 90 m^2 PV area. Fig. 5.13 (a), (b) and (c) show the variation of total capital cost, annual maintenance cost and payback periods for the Mono, Poly and Thin film type cells. The packaged air conditioner powered by grid power is assumed as the reference system cost. Fig 5.13 a shows that as the total investment cost decreases the difference between the capital cost of the solar photovoltaic and reference system also reduces consequently the annual maintenance costs also reduces leading to lower payback periods.

It is observed from the fig 5.13 c that as the cost of total investment is decreased by 50 % the payback period also decreases and comes down to 8.2 year for mono, 8 years for poly and 6.9 years for thin film cells . At present costs in India, the payback periods is 18 years, 17.7 years and 14.9 years for Mono, Poly and Thin films respectively for the same considered case in the warm and humid climate.



(a)



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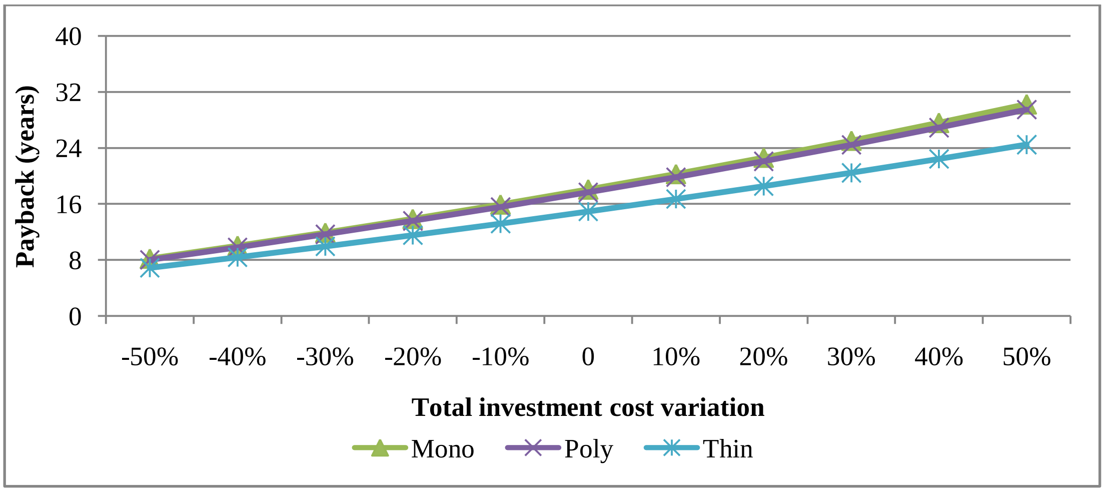


(c)

Fig 5.13 Influence of total investment cost variation on (a) Total capital cost (b) Annual maintenance cost (c) Payback time (PV area -90 m^2, warm and humid climate)

5.5.2 Electricity cost sensitivity analysis

In India major part of electricity is generated by power plants using fossils fuel. The hike in the price of fossil fuels leads to continuous hike in the electricity cost. At present electricity cost the solar photovoltaic cooling system (grid supported) is not feasible for only cooling purpose. But with the increase in the price of electricity this system may become feasible. In order to see the effect of electrical prices sensitivity analysis is presented here.

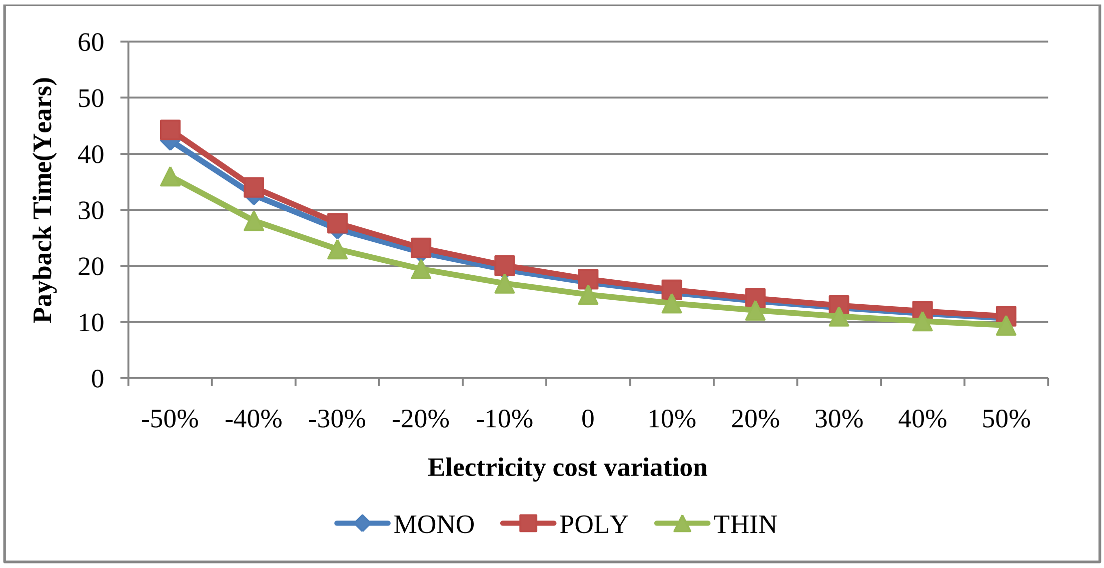


Fig 5.14 Influence of electricity prices on payback time

(PV area -90 m^2, warm and humid climate)

Here the effect on payback time is carried out for +50 % increase and 50 % decrease in prices of electricity. Fig 5.14 shows the effect of electricity cost on payback time. It has been observed from the fig.5.14 that as the electricity cost increases the annual net savings also increase thus the payback time decreases. In future, if the electricity prices are increased by 50 % then the payback time will come down to 10.7, 11, 9.4 years for the mono, poly and thin film cells respectively. Thus we observe that if the investment cost is lowered down or electricity prices are hiked then the payback time can reduce considerably.

The investment cost is more sensitive than the electrical prices. A reduction of 50 % in investment cost has reduced the payback time approximately 55 % while increase in the electrical prices by 50% reduced the payback time by 37%.

In future if investment cost lowers down to 50 % then the effect of electricity prices on payback time is shown in the fig 5.15 for the same considered cases in the warm and humid climate. It has been observed from the fig.5.15 that as the cost of electricity is increased in future the payback time is reduced considerably.

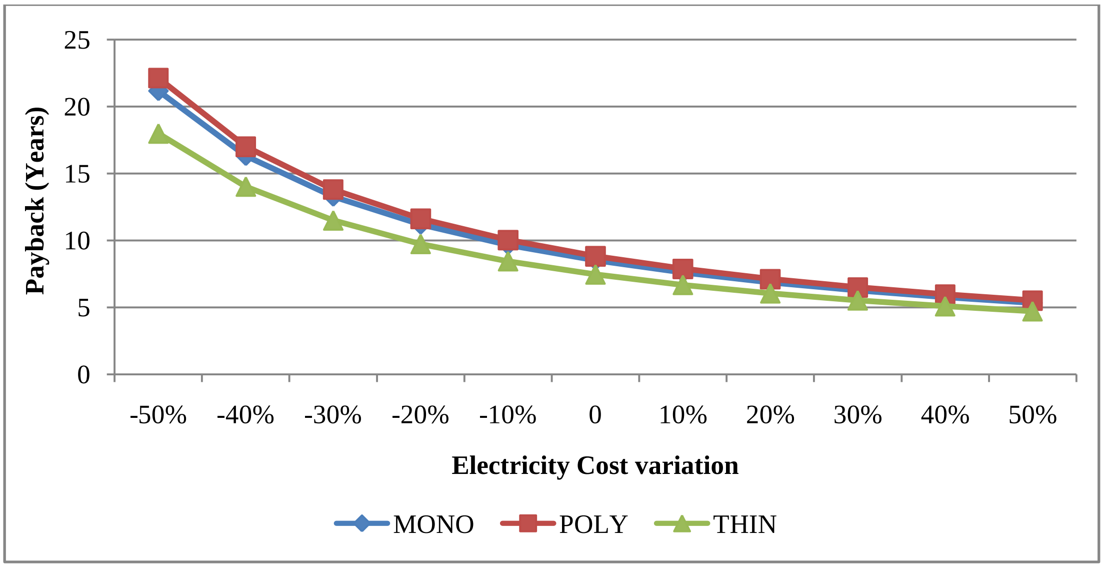


Fig 5.15 Influence of electrical prices on payback time

After 50 % reduction in the investment cost the payback period is considerably lower in the range of 8-10 years with the present electricity cost, however if the cost of electricity is increased simultaneously by 50% then the payback period comes down to 5 years.

5.6 Summary of Chapter

It can be conclude from the performance analysis of the solar photovoltaic cooling system that it is technically feasible because it offers solar fraction in the range of 0.32-0.60 in the considered climates and PV areas (Grid supported system). The system also offers the primary energy savings up to 60 % in the considered climate and PV area in this study.

Financially with the present cost structure in India the solar photovoltaic cooling system (Grid supported) has higher payback in the range of 14-26 years. The highest payback period is in the moderate climate due to the low cooling demand of the building resulting into low utilization of system. When PV based systems are optimally used with net metering provisions during the non cooling periods then the payback period is 4-6 years for all climatic zones.

CHAPTER 6 COMPARISON OF SOLAR THERMAL AND SOLAR PHOTOVOLTAIC COOLING SYSTEMS

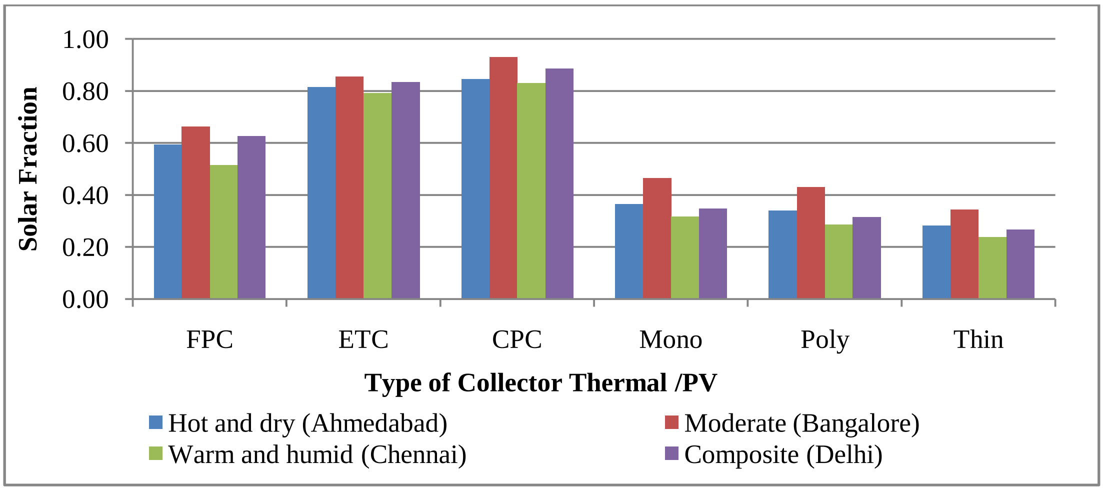
In this chapter technical and financial comparison of solar thermal and solar photovoltaic cooling system is presented. Systems are compared on the basis of solar fraction, primary energy savings and electrical (Grid) COP are compared and financially payback period and internal rate of return are compared.

6.1 Technical Comparison

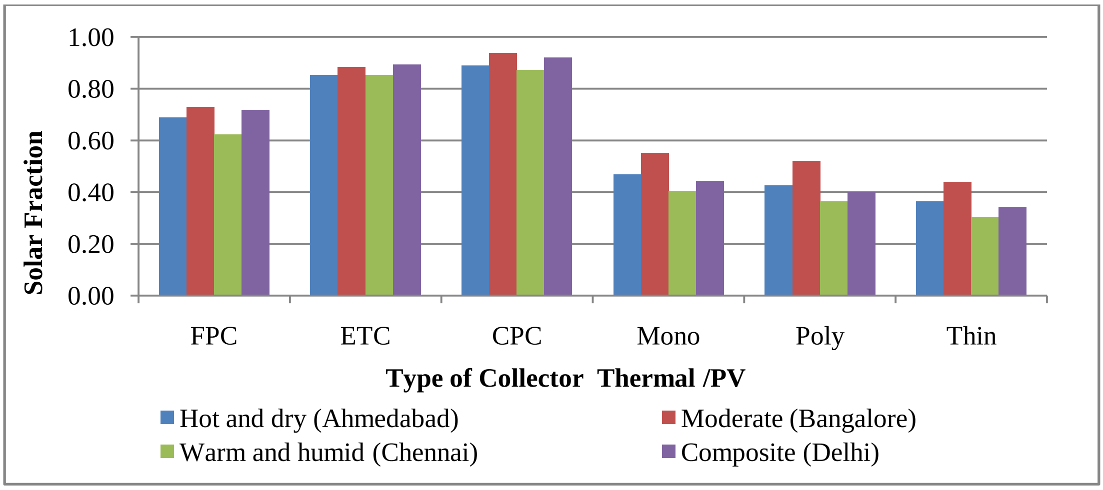
In this section technical comparison of solar thermal and solar photovoltaic cooling system, based on solar fraction, primary energy savings and electrical (Grid) COP are presented and discussed.

6.1.1 Solar fraction

The annual solar fraction for thermal and photovoltaic cooling system is compared for the lowest, highest and medium size collector/ PV areas. Fig 6.1 (a), (b) and (c) show the comparison of annual solar fraction for thermal and photovoltaic cooling system using 70, 90 and 110 m^2 collector/PV areas respectively. It has been observed from the fig.6.1 that the solar fraction is higher for the solar thermal cooling system in all type of collectors than the solar photovoltaic cooling system in the considered climates and collector areas. However at lower collector area the annual solar fraction is high for the ETC and CPC type collector and low for the FPC, Mono, Poly and Thin film. As the collector area increases the annual solar fraction rapidly increases in the case of FPC, Mono, Poly and Thin film cells but in the ETC and CPC only a marginal change occurs. In the case of solar thermal cooling system, annual solar fraction either marginally increases or reaches an optimized state with the increase in collector area while in the case of solar photovoltaic cooling system the annual solar fraction rapidly increases with the PV area. In the solar thermal cooling system the solar fraction reaches 94 % in the moderate climate whereas in the solar photovoltaic cooling system it is 60% in the moderate climate.



(a)



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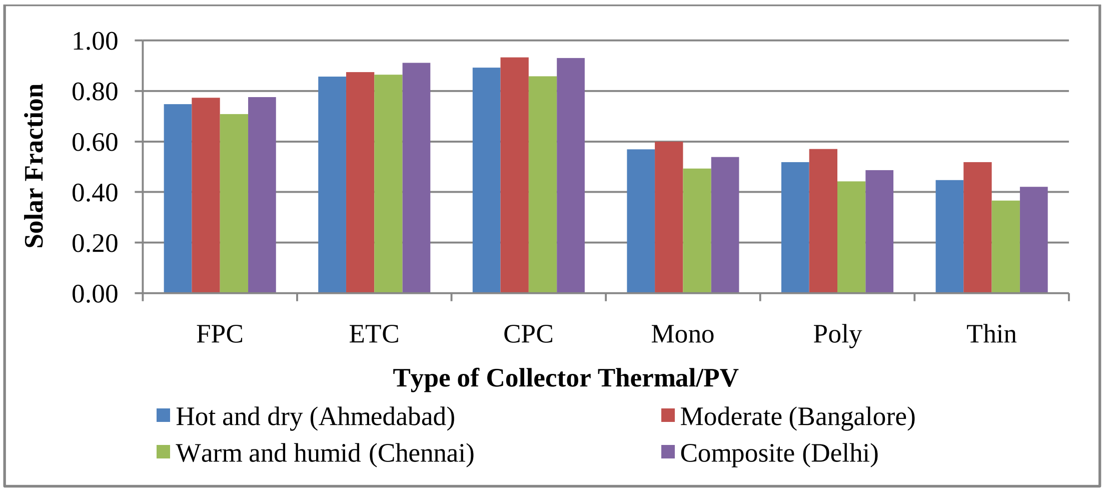


(c)

Fig.6.1 Annual solar fraction comparison for thermal and photovoltaic cooling (a) 70 m^2 (b) 90 m^2 (c) 110 m^2

The solar fraction is lowest for the warm and humid climate in both type of cooling systems and highest in moderate climate.

The solar fraction is lower in the case of solar photovoltaic cooling system than the solar thermal cooling system because in the thermal cooling system there is a storage device (hot storage tank) between the solar thermal collector and cooling machine resulting in continuous operation of vapour absorption machine without using the grid power for small fluctuation in solar radiations. In the solar photovoltaic cooling system the annual solar fraction is calculated without considering the storage device. The vapour compression machine (Packaged air conditioner) requires a fix amount of power to drive the compressor, if instantaneously it is available on PV it is supplied to the cooling system otherwise it is taken from the grid and not accounted for the annual solar fraction.

In solar thermal cooling system the annual solar fraction increases up to an optimum collector area and after a certain value heat losses increase resulting in lesser annual solar fraction whereas in the case of solar photovoltaic cooling system any increase in the PV area increases the annual solar fraction (Fig.6.2).

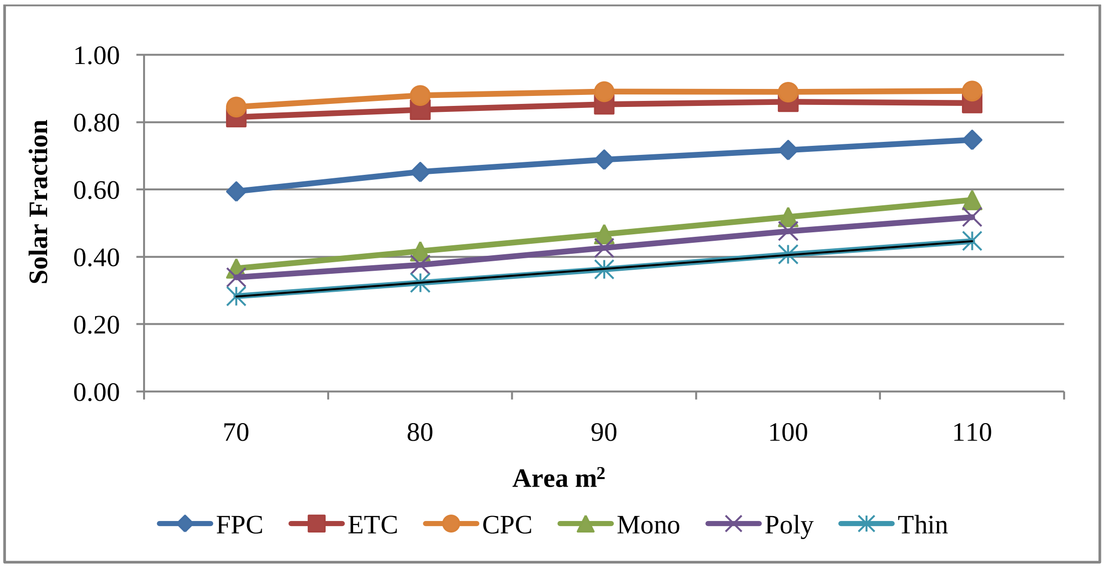


Fig. 6.2 Annual solar fraction comparison - Hot and dry climate (Ahmedabad)

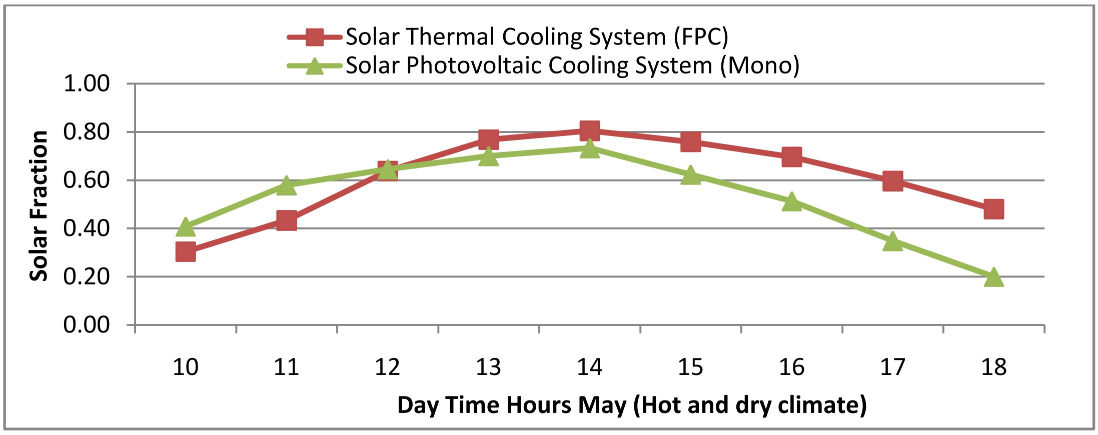


Fig 6.3 Hourly Comparison of solar fraction of STCS and SPCS

Fig 6.3 shows the hourly comparison of solar thermal cooling system (STCS) and solar photovoltaic cooling system (SPCS). It has been observed from the fig 6.3 that the in the morning hours the solar fraction is higher for the solar photovoltaic cooling system than the thermal cooling system. In the STCS the working fluid in the solar collector required time to heat up while in the SPCS the power generation is instantaneous. In the noon hours the solar fraction of PV system and thermal system is approaching the same value. In the afternoon hours the solar fraction of thermal system is significantly high in comparison to the PV system because in late hours the solar radiation decreases and power generation from PV is decrease resulting in low solar fraction while in the solar thermal cooling system the backup is supported by the hot storage tank. In the afternoon hours decrement in the solar fraction is low in the thermal cooling system than the PV system.

The STCS possesses solar fraction above 60% during the 12:00PM to 17:00 PM because it is supported by the storage tank while in the PV system it is sharp decreases. If we provide storage system in the PV than the solar fraction will also high. During the day time there is some moment when the compressor was turned OFF by the thermostat, at this particular moment the power consumption by the compressor is zero. If the power generation by PV at these moments is stored than it will be utilized in the evening hours.

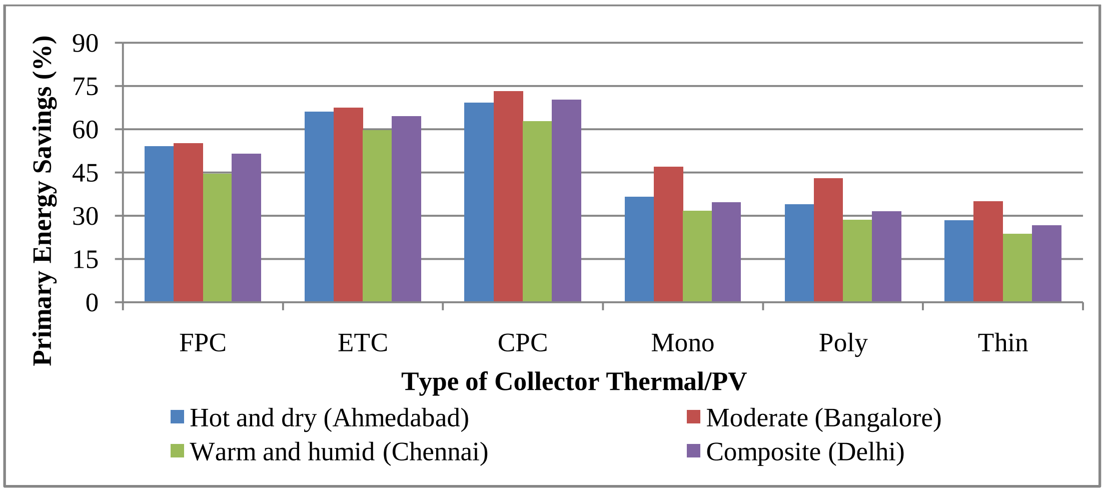
6.1.2 Primary energy savings

Fig 6.4 (a), (b), and (c) show the primary energy saving for the solar thermal and solar photovoltaic cooling system (grid supported) in the considered climate with the 70, 90 and 110 m^2 thermal/PV collector area respectively. In the case of solar photovoltaic system the primary energy savings are considered without net metering. It has been observed from the fig.6.4 that at 70 m^2 collector area the primary energy savings are lower in solar photovoltaic cooling system than the solar thermal cooling system. As the collector area increases the primary energy savings also increase rapidly in the solar photovoltaic cooling system than the thermal cooling system.

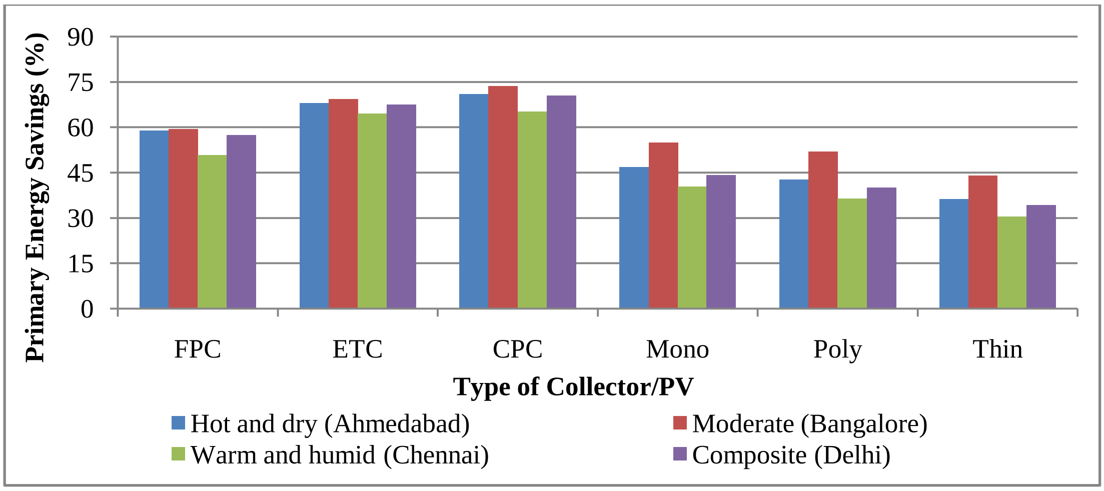
Similarly to the solar fraction the primary energy savings also reach optimized state in the solar thermal cooling with the ETC and CPC types of collectors. In the FPC, the primary energy savings increasing with the collector area show that there is scope for increase in the collector area than used here (70-110m^2).

In the solar photovoltaic cooling system the primary energy savings are highest with the mono cells and lowest with the thin film cells. This savings are less than the solar thermal cooling in all the climates and areas considered here. The power generation by PV is partially used in cooling and if not demanded by the air conditioner it is dumped so it does not contribute in savings of primary energy savings. However any increase in the PV area will increase the primary energy savings in the case of solar photovoltaic cooling system.

In the solar thermal cooling system collector area is optimized between 90-110 m^2 in all climates with ETC and CPC type resulting in either constant or even decrease in the primary energy savings. The highest level of primary energy savings reaches 74% and 60% for the solar thermal and photovoltaic cooling system respectively for the climates and collector areas considered here.



(a)



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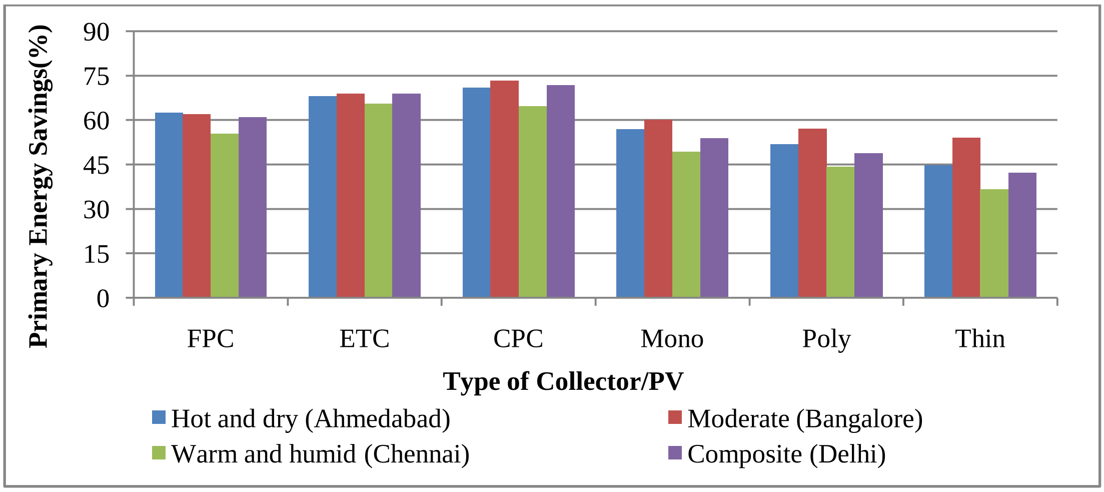


(c)

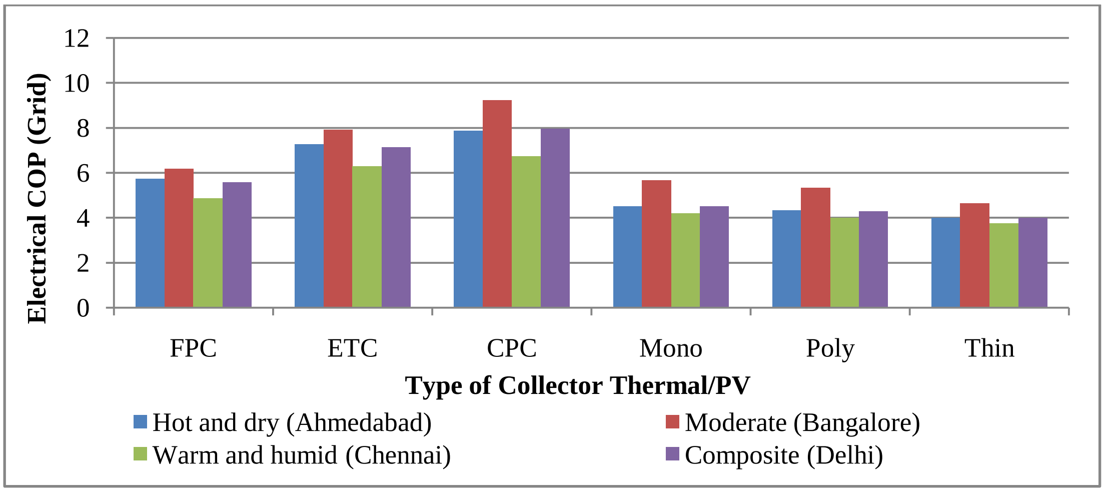
Fig.6.4 Primary energy savings comparison for solar thermal and photovoltaic cooling (grid supported) (a) 70 m^2 (b) 90 m^2 (c) 110 m^2

6.1.3 Electrical (Grid) COP of system

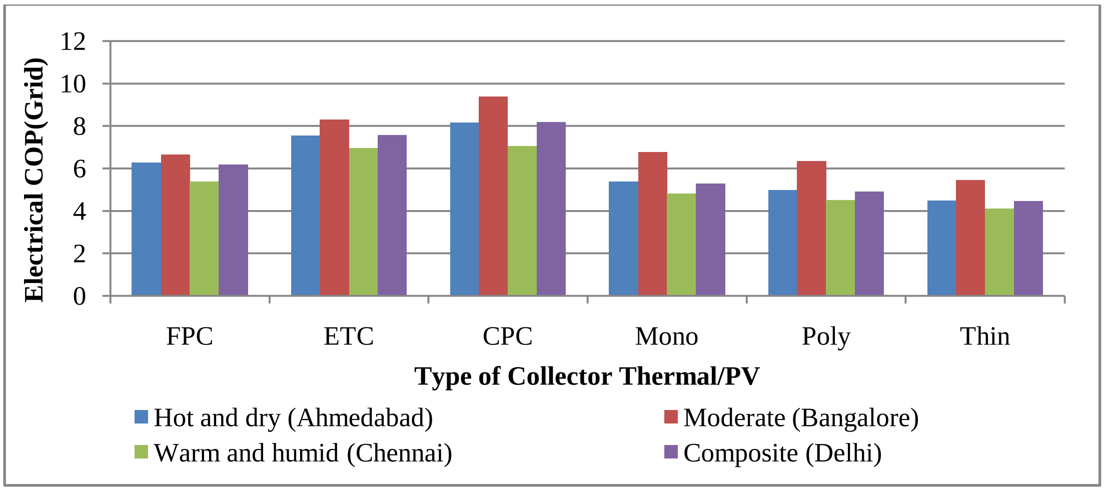
The electrical (Grid) COP is calculated on the basis of total annual cooling demand of the building and total grid power consumption to fulfill this demand. It is the ratio of annual cooling demand of building to the grid power consumption. Fig 6.5 (a), (b) and (c) show the comparison of electrical (Grid) COP for the solar thermal and solar photovoltaic cooling system. It has been observed from the fig.6.5 that the electrical (Grid) COP is higher for the solar thermal than the solar photovoltaic cooling system in the all the climates at 70 m^2 thermal/PV area. Any increase in the thermal/PV area increases electrical COP marginally in the case of solar thermal especially in ETC and CPC but we observe a rapid increase in the solar photovoltaic. In solar thermal cooling system the electrical (Grid) COP ranges between 4.87-7.01, 6.29-8.22 and 6.74-9.32 for the FPC, ETC and CPC respectively.

At higher collector area of 110 m^2 the electrical (Grid) COP of solar photovoltaic cooling system is comparable with the FPC and reaches 7.58 in the moderate climate (Bangalore) with 110 m^2 collector area. It ranges 5.67-7.58, 5.32-7.08 and 4.64-6.31 for the mono, poly and thin film respectively.

The COP of packaged air conditioner is ranging between 2 and 3 depending on climatic conditions. Coupling photovoltaic with the packaged air conditioner increase COP and reaches up to 7.58 in the moderate climate (Bangalore) with the 110 m^2 PV area.



(a)



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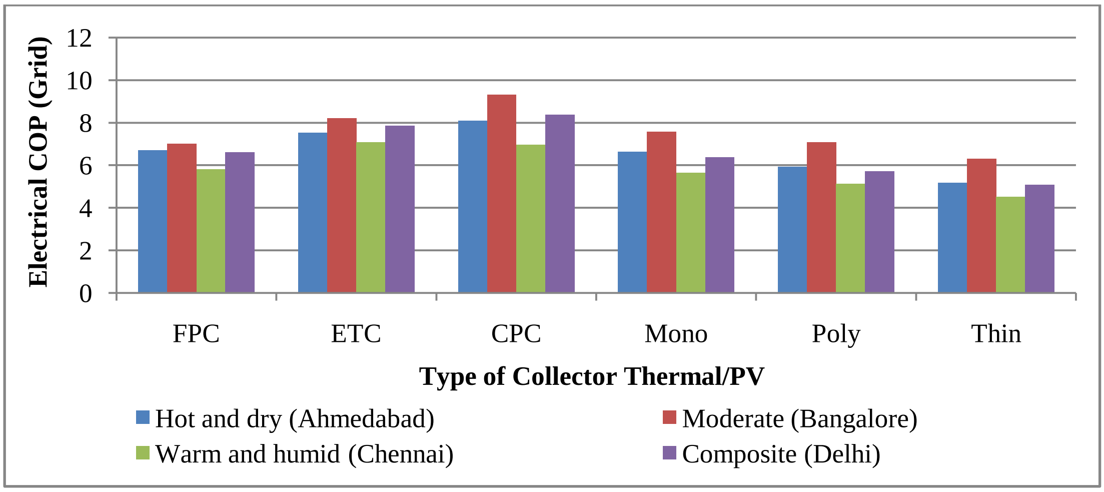


(c)

Fig.6.5 Electrical (Grid) COP comparison for solar thermal and photovoltaic cooling (grid supported) (a) 70 m^2 (b) 90 m^2 (c) 110 m^2

6.2 Economical Comparison

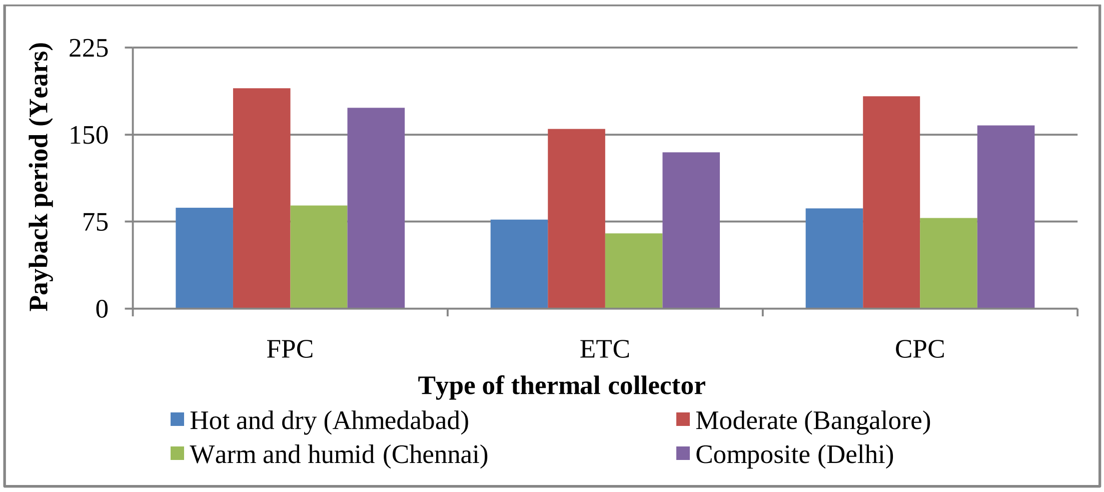
In this section economical comparison of solar thermal and solar photovoltaic cooling systems based on payback period and IRR are presented and discussed.

6.2.1 Payback periods

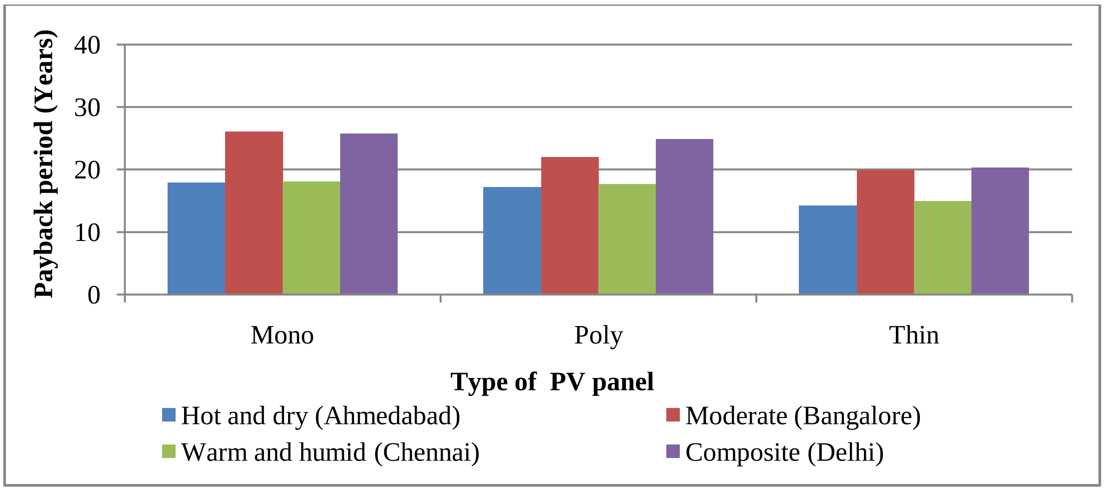
The economical comparison of solar thermal and photovoltaic cooling is carried out on the behalf of payback period and IRR calculations. Fig.6.6 (a) (b) and (c) show the payback period for the solar thermal, solar photovoltaic and solar photovoltaic (with net metering) cooling systems respectively.

It has been observed from the fig.6.6 that the payback period is higher for the solar thermal cooling system in the entire considered climates than the solar photovoltaic cooling system because in the solar thermal cooling system investment cost is very high. Also in this system the absorption chiller has an additional cost of Rs 18 lac that is not in the case of solar photovoltaic cooling system. The maintenance cost is linked with capital cost resulting in the higher maintenance cost and lower annual savings for the solar thermal cooling system against a high investment. In the solar thermal cooling system the highest payback period is in the moderate climate due to the low cooling demand of the building with the same investment and lowest payback period is for the warm and humid climate i.e. 65 years with the ETC type collector.

Like solar thermal, solar photovoltaic cooling system (without net metering) also has a high payback period, however it is significantly lower than solar thermal system. The lowest payback period 14 years is found for hot and dry climate (Ahmedabad) due to good combination of cooling demand and annual electricity generation, for moderate climate (Bangalore) payback period is highest i.e. 26 years. When PV based systems are optimally used with net metering provisions during the non cooling periods then the payback period is 4-6 years for all climatic zones.



(a)



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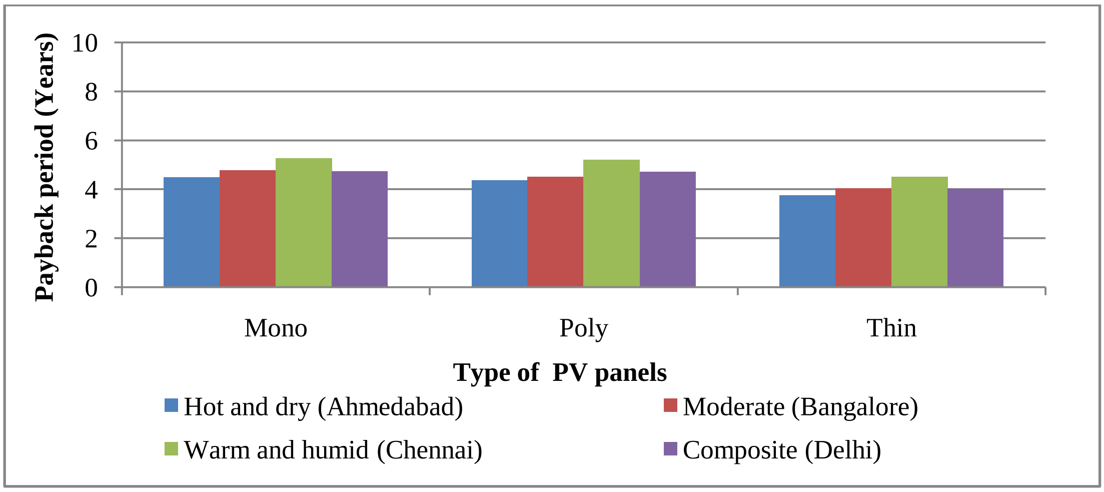


(c)

Fig.6.6 Payback periods (a) Solar thermal (b) Solar photovoltaic (Grid supported) (c) Solar photovoltaic (Net metering)-Collector/PV area-90m^2

6.2.2 Internal rate of return

The internal rate of return is negative in the case of solar thermal cooling system. It shows that the solar thermal cooling system is not feasible in any climate with present cost structure in India. The value of IRR ranges between -10.8% to -13.9 % in the considered climates and collector areas. The high initial cost, high annual maintenance cost and low annual savings are responsible for the negative value of IRR. The difference between cost of absorption chiller and packaged air conditioner is very high in India in comparison to other countries is also responsible for negative value of IRR.

In the solar photovoltaic cooling system (Without net metering) the IRR is also negative in most cases (0.41% and -7.41%) expect in the hot and dry climate with the thin film cells. It has a very low value of 0.41%. The reason is the high initial cost and low solar fraction.

In the solar photovoltaic cooling system with net metering the whole power generated by PV is used either by the air conditioner or supplied to the grid. The net amount of power is the balance of electricity exchange between consumer and public grid. In this way the IRR has the higher value in the range of 13.9%-21.3% depending on the climates and type of cells.

CHAPTER 7 PERFORMANCE ENHANCEMENT OF PV COOLING SYSTEM

In the last chapter we have seen that the achieved solar fraction of solar photovoltaic cooling systems is significantly lower than the solar thermal cooling systems. In the Solar thermal cooling system there is a storage device (hot storage tank) between the solar thermal collector and cooling machine resulting in continuous operation of vapour absorption machine without using the grid power for small fluctuation in solar radiations. Solar photovoltaic cooling system with battery storage is not analysed because initial analysis shows that the capital cost of storage system is very high and it is also linked with annual maintenance cost. System also requires reoccurring cost at every 4-5 year for replacement of batteries. In the solar photovoltaic cooling system the annual solar fraction is calculated without considering the storage device. The vapour compression machine (Packaged air conditioner) requires a fix amount of power to drive the compressor, if instantaneously it is available on PV it is supplied to the cooling system otherwise it is taken from the grid and not accounted for the annual solar fraction.

In the present chapter various analyses are carried out for increasing the solar fraction using different techniques. The main ingredients of solar photovoltaic cooling system are photovoltaic panels cooling system and building. So the solar fraction can be increased by increasing the power generation from the photovoltaic these techniques are single axis tracking and double axis tracking mechanism. In the cooling system side solar fraction can be increase by using VRF in place of PTAC and in the building, cooling load may be reduced by using thermal masses. In this chapter analysis is carried out using mono crystalline cells for being most efficient and modeling and simulation results are presented and discussed.

7.1 Tracking Systems

Tracking systems that adjust the position of PV modules in the direction of the sun can boost yields from solar installations by 40% or more. Two basic configurations for tracker systems are available. Single-axis trackers rotate about one axis, azimuthally orienting the panels to track the sun's movements over the course of a day. Dual axis trackers provide both azimuth rotation for daily tracking and tilt rotation for seasonal tracking the movement of the sun. Nordic (India) offers standard single and dual axis tracking products for commercial applications (kW scale). These trackers are mounted on a galvanized steel pole structure and use PLC driven linear actuators/worm gears to orient the PV panels and track the sun. The trackers are built in such manner to protect the panels if the wind speed is too high. The trackers can accommodate solar PV modules upto 25 sq. m [139].

7.1.1 Tracking system modeling

In the TRNSYS model of solar photovoltaic cooling system, the tracking system is enabled in the weather file Type 15.3 parameter 7 that allows the model to track the sun. Fig 7.1 shows the annual power generation for the four climates with three options fixed, single axis tracking and double axis tracking systems. It has been observed from the graph that the annual power generation increases about 10-20% using single axis tracking and 5-15% using double axis tracking mechanism.

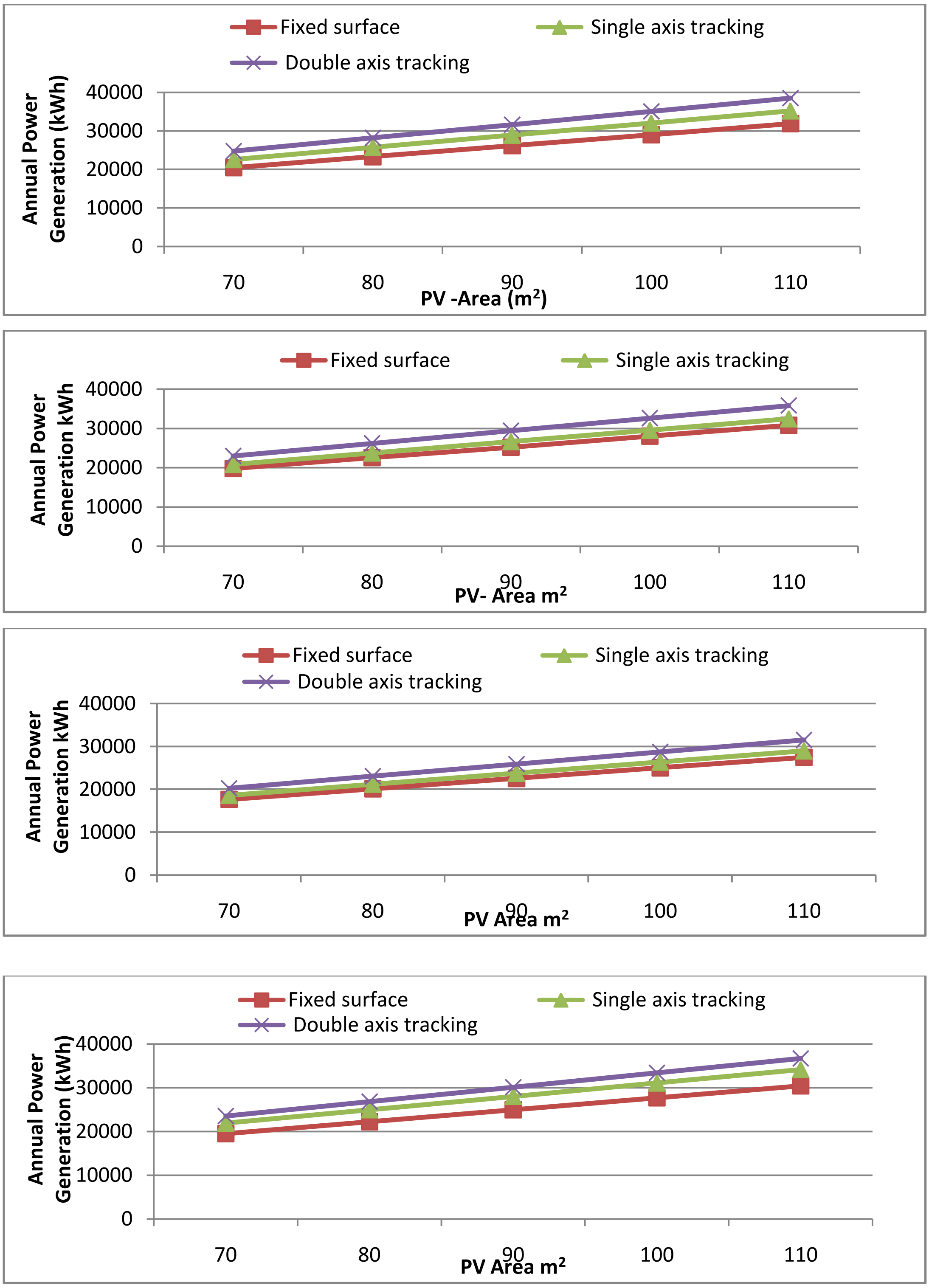


Fig.7.1 Annual power generation with PV area (a) Hot and dry (Ahemdabad) (b) Moderate (Bangalore) (c) Warm and humid (Chennai) (d) Composite (Delhi)

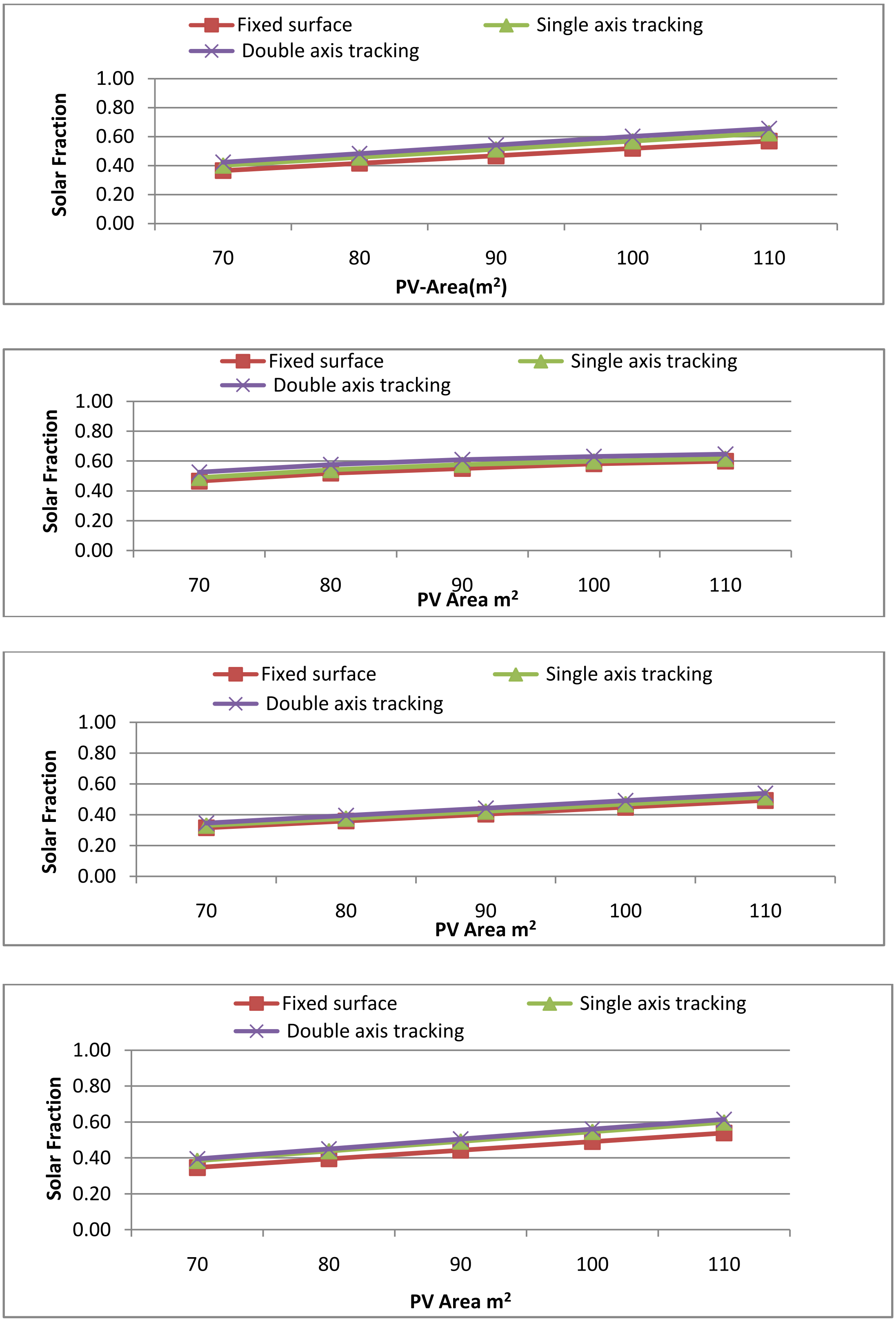


Fig.7.2 Annual Solar Fraction with PV area (a) Hot and dry (Ahemdabad) (b) Moderate (Bangalore) (c) Warm and humid (Chennai) (d) Composite (Delhi)

7.1.2 Performance analysis of PV cooling system with tracking

In this section performance analysis of PV cooling system with tracking of photovoltaic cells are presented and discussed.

Solar fraction

Fig 7.2 shows the solar fraction for the four different climates with the three options fixed, single and double axis tracking. It is clear from the fig 7.2 that the solar fraction increases because the power generation increases while the energy consumption is same in all the three case i.e fixed, single and double axis tracking. So there is more matching between generation of PV and consumption of air conditioner.

Electrical COPs

Fig 7.3 shows the comparison of electrical COP for the four different climate zones at PV area of 90 m^2. It has been observed from the fig 7.3 that the electrical COP is highest when using the double axis tracking mechanism. This is due to higher power generation from the PV when it is mounted on dual axis trackers. The power generation increases but power consumption remains same as in the fixed, resulting in more matching between power generation and consumption and this decreases the power consumption from grid.

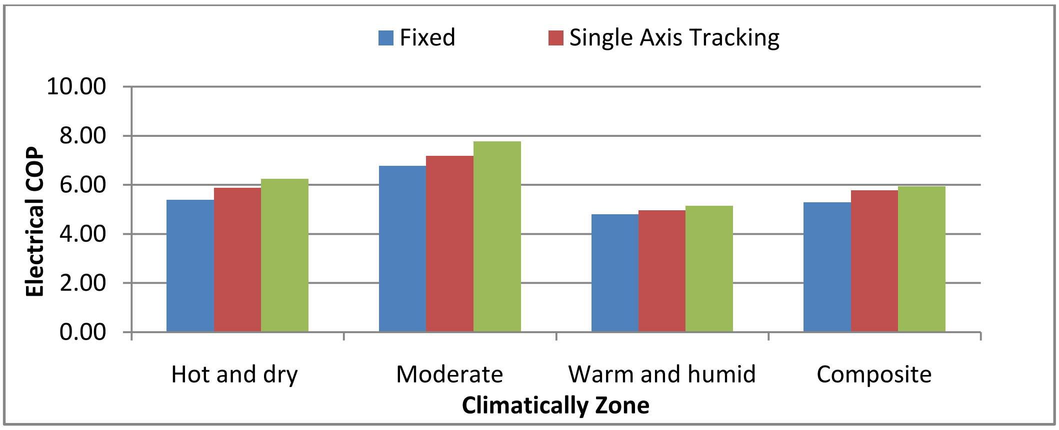


Fig 7.3 Comparison of Electrical COP (PV area-90 m^2)

Payback Time

Fig 7.4 shows the comparison of payback time for the fixed, single axis and double axis tracking mechanism with respect to the different climates. It has been observed from the fig 7.4 that the payback time is very high in the tracking systems because the cost of tracking is very high Rs. 8370/m^2 of PV area [139]. The annual power generation increases about 15-35% while the cost of tracking system increases very high (Rs.8370/m^2). The highest payback time is for the moderate climate because of the low cooling demand.

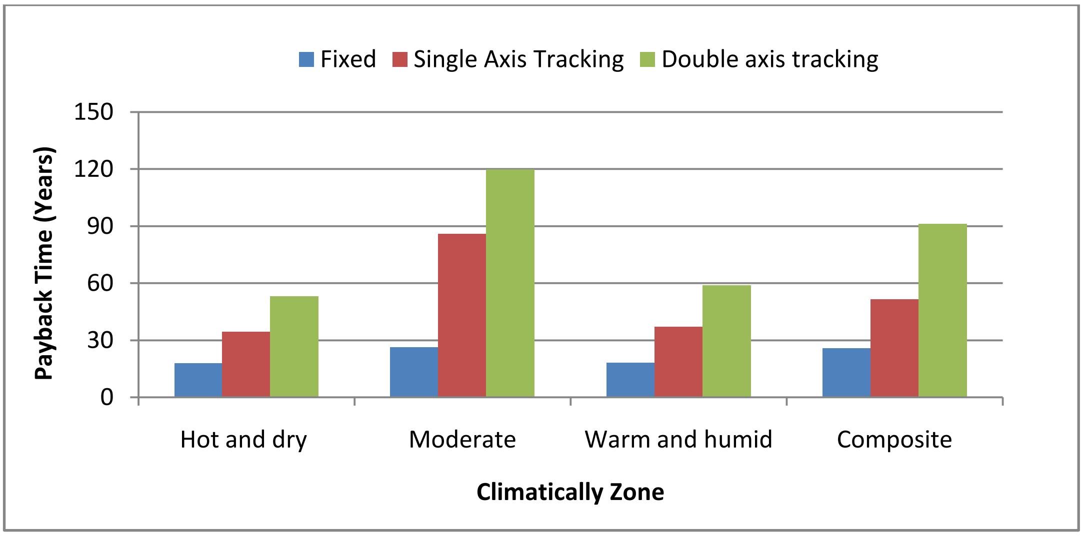


Fig 7.4 Comparison of Payback time (PV area90 m^2)

7.2 Thermal Mass

Thermal mass can reduce indoor air temperature variation in buildings. Indoor air temperature is mainly influenced by external climatologically parameters (solar radiation, outdoor temperature) and highly variable internal loads (human activity, lights, equipment). During the summer, this results in temperature variation, with peaks occurring around noon hours. To reduce indoor air temperature and cooling load peaks, and to transfer the load to a later time in the day, it is possible to store heat in the material of the outer envelope and the interior mass of the building. The storage material is the construction mass of the building itself, which is referred to as thermal mass. It is typically contained in walls, partitions, ceilings and floors of the building, constructed of material with high heat capacity, such as poured concrete, bricks and tiles. Thus Thermal mass is defined as any building material having a high heat storage capacity that can be integrated into the structural fabric of the building to effectively utilize the passive solar energy for the purposes of heating and cooling. The selection of a particular material to function as thermal mass depends on variety of factors such as a high density (ρ), a high specific heat capacity (C_p) and the ability to delay the time taken to release the heat [Siddiqui O. 2009].

7.2.1 Thermal mass modeling

In this work the building construction was done layer by layer. The properties of each material used in construction are shown in the Appendix D. The material is defined with the specific heat capacities and density that incorporate the thermal mass. In order to enhance the solar fraction for PV cooling technologies it is reasonable to see the effect of the thermal mass. The present case is called the base case and further improvement in the thermal mass is denoted as thermal mass-1, 2, and 3.

Base Case	The material thickness and properties shown in the table 3.3 and appendix D
Thermal mass-1	Change in the density of brick from 750kg/m^3 to 1500 kg/m^3
Thermal mass-2	Change in the density of brick from 750kg/m^3 to 1500 kg/m^3 and Change in thickness of brick 220 mm to 300mm in the wall construction.
Thermal mass-3	Change in the density of brick from 750kg/m^3 to 1500 kg/m^3. Change in thickness of brick 220 mm to 300mm in the wall construction and Change in the thickness of concrete slab 210 mm to 300 mm in the roof construction.

Building geometry was updated by incorporating the thermal masses and annual cooling energy demand and peak cooling energy demand was calculated by the building cooling load simulation using different type of building having the different thermal masses.

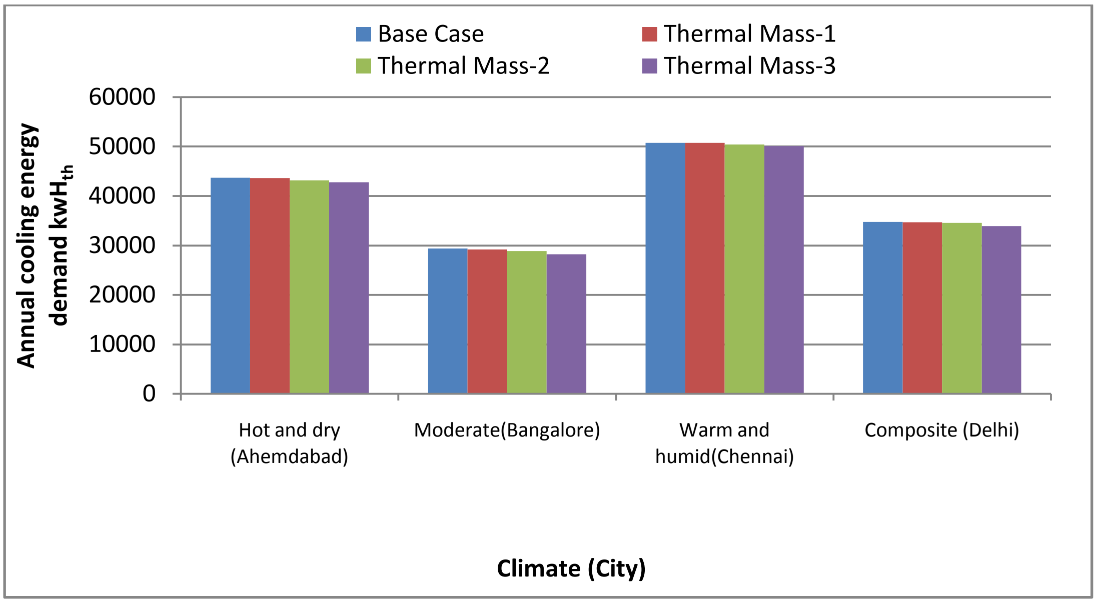


Fig 7.5 Comparison of Annual Cooling Energy Demand

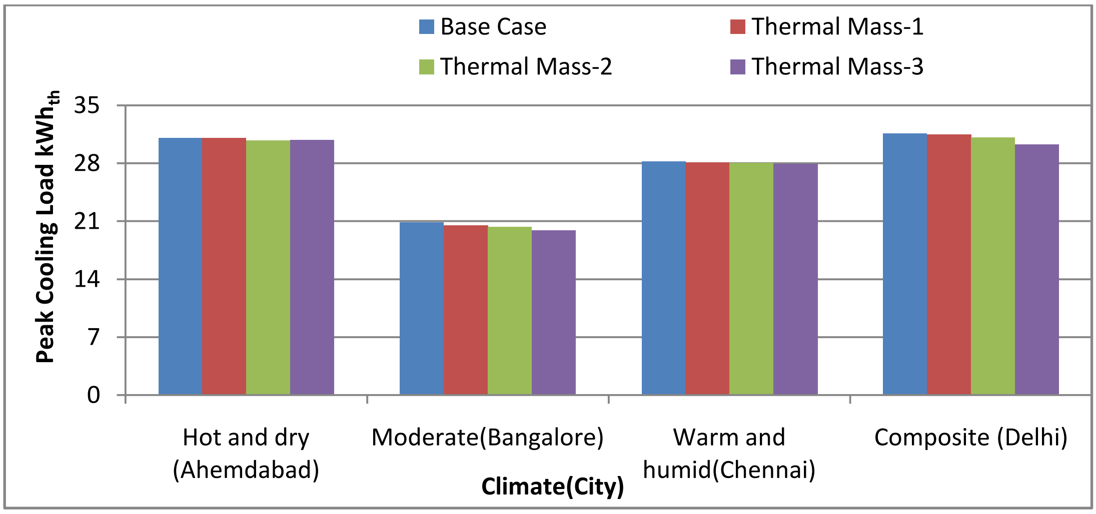
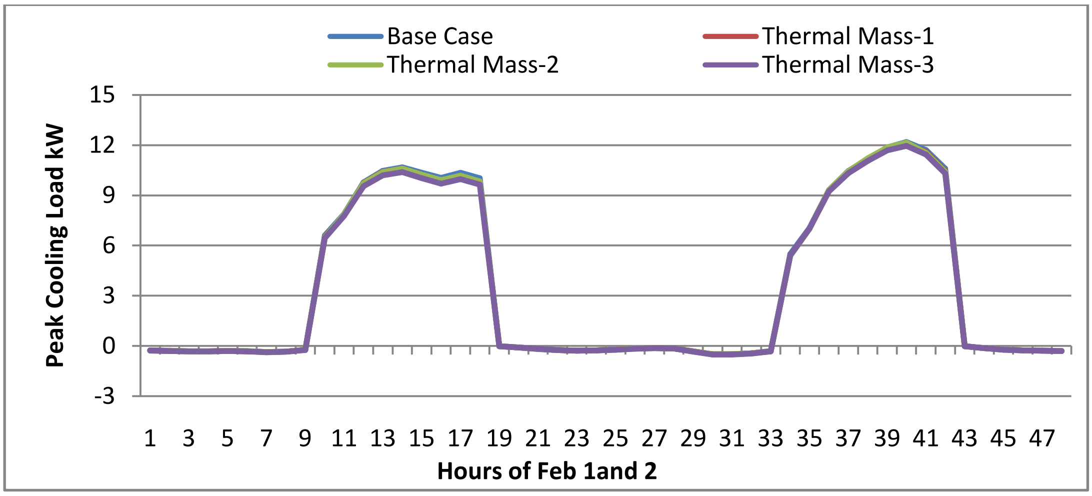


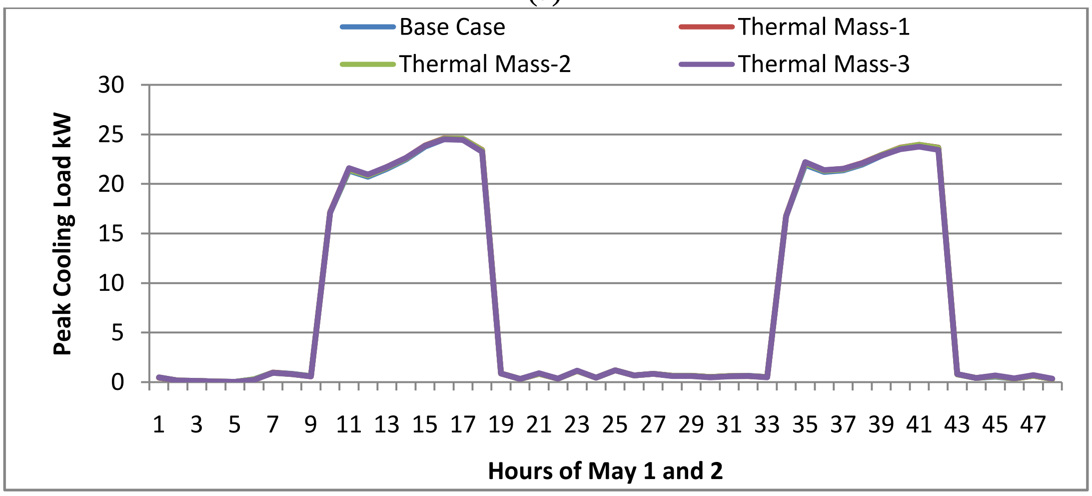
Fig 7.6 Comparison of Peak Cooling Load

Fig 7.5 and 7.6 show that the annual cooling energy demand and peak cooling load for the four climate zones with the thermal masses. It has been observed from the Fig 7.5 and 7.6 that the annual cooling energy demands and peak cooling loads were decreased in all climates. The building envelope has the insulation in the base case as well as in the thermal masses case that prevent the solar heat to enter inside. Higher thermal masses on the external wall/roof of the building slightly delay the peak cooling load of the building and decrease the annual cooling energy demand of the building. The effect of thermal mass on annual cooling energy demand is very low because the building envelope area is less and building envelope has the high internal gain during the occupancy hours [900-1800].

In the hot and dry climates when the ambient temperature is relatively high during the night time the stored heat radiates back to the ambient is not completely possible and this heat energy also penetrates in the building envelope resulting in the demand of higher cooling energy specially in the months of summer. The effect of thermal masses in the moderate climate is higher than the other climates. The results are good agreed with the [Zhu L et al. 2009].



(a)



(b)

Fig 7.7 Hourly profile of peak cooling load for hot and dry climate
(a) Feb 1/2 and (b) May 1/2

Fig7.7 a and b shows the hourly profile of the peak cooling load for the month of February and May for hot and dry climate (Ahemdabad). It has been observed from the fig that the effect of thermal mass is negligible in both conditions.

7.2.2 Performance analysis of PV cooling system with thermal mass

In this section performance analysis of PV cooling system using thermal masses are presented and discussed.

Solar Fraction

Fig 7.8 shows the annual solar fractions for the different climate zones and thermal masses. It has been observed from the fig.7.8 that the effect on solar fraction by using additionally thermal mass is negligible within 1-2% only. It is highest in the moderate climate. The size of air conditioning system is same as in the base case because the peak cooling load is reduced only 0.9 kW in the moderate climates. The peak cooling is reduced to 0.3-0.5 kW in other climates. It is not feasible to reduce the size of the air conditioning system because the reduction in size negligible as per market conditions.

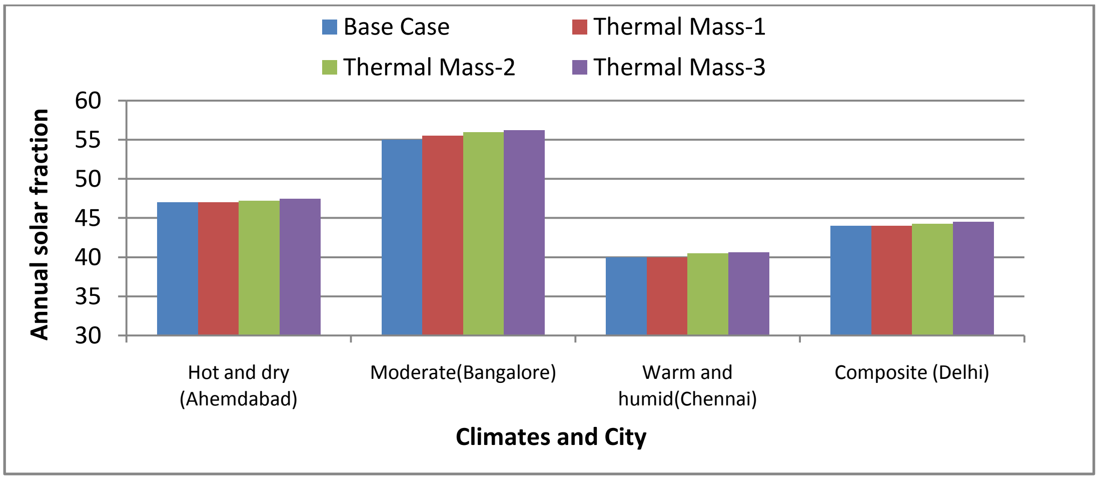


Fig 7.8 Comparison of solar fraction for different climates with thermal masses

The main reason behind no increase in the annual solar fraction by using additional thermal mass is because in base case thermal mass is already there and secondly building envelope has high insulation that prevents the flow of heat from ambient to inside.

7.3 Modifying Air Conditioning System Sizing Approach

The annual power consumption of photovoltaic operated air conditioner may be decrease by change in control strategy i.e operation of photovoltaic air conditioners. PV based air conditionering cooling system works during the office hours i.e. 09:00 -18:00. In the event that the building is unoccupied during the evening hours, like office buildings, it is possible to relax the restrictions on indoor thermal comfort. In any event, outdoor conditions are more favourable for passive cooling techniques, like natural, hybrid or indirect ventilation, which can be used to remove portions of the load [Singh A.P 2012]. The cooling system may be switched off for 1 or 2 hours before the closing of office and in that time the thermal comfort may be achieved by natural ventilation and ceiling fans. In the evening hours when the cooling system is off than the PV generated power supplied to cooling system is also zero, and this power is either feed to the grid or dumped. Thus this operation may decrease the annual power consumption but it will not increase the solar fraction.

The other way to increase the annual solar fraction is by reducing the size of the air conditioner. Marc 2010 reported that in the case where the air conditioner is undersized and runs in nominal conditions with good performances, thermal comfort inside the building will not be achieved in some critical periods of the year. In this case thermal comfort can be achieved with ceiling fans [O Marc2010]. Before applying this option cooling load analysis and thermal comfort condition must be analyzed.

7.3.1 Analysis of Peak Cooling Load Hours

In the chapter 3, Fig 3.14 shows the monthly peak cooling load variation of four climate zones. It has been observed from the fig 3.14 that the peak cooling load occurs in few hours in a year. Fig. 7.9 shows the annual load duration curve for four climates. It has been observed from the curve that the peak cooling load greater than 9 TR (31.5kW) in year in the composite climate is one hour only. The peak cooling load greater than 8 TR (28 kW) is only 24 hours in hot and dry climate (Ahmedabad), 1 hours in warm and humid climate (Chennai) and 24 hours in composite climate (Delhi). Similarly the peak cooling load greater than 7 TR (24.5kW) is also less than 300 Hours in any climate. In the moderate climate the peak cooling load greater than 5 TR (17.5kW) is only 44 hours. Hence in this condition the sizing of air conditioner may modified and fix 7 TR (24.5kW) for the hot and dry, warm and humid and composite climate and 5 TR for the moderate climate.

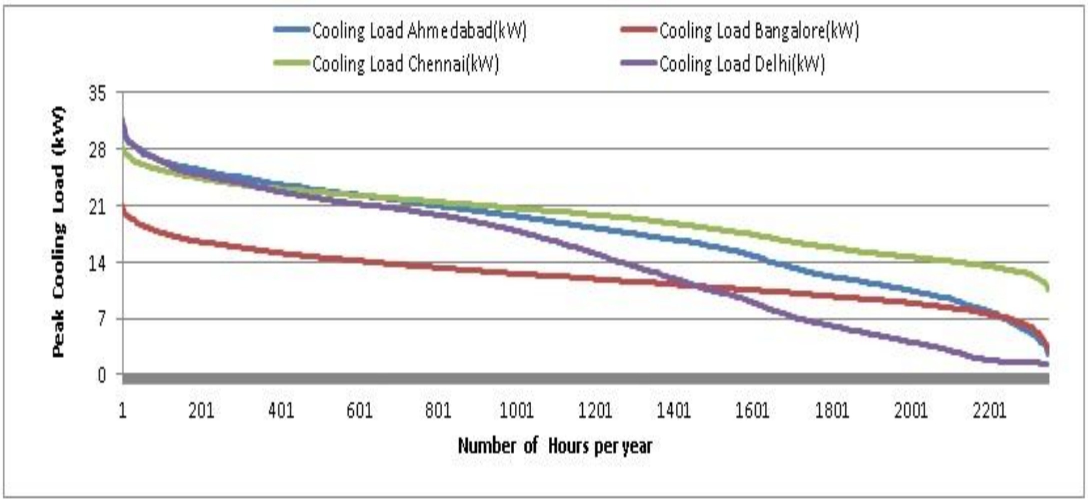


Fig. 7.9 Annual Load Duration Curve

7.3.2 Utilizing high air velocity

The decrease in the size of air conditioner reduces the thermal comfort inside the building. In this case the thermal comfort in the building can be achieved by air movement. However the precise relationships between increased air speed and improved comfort have not been established. ASHRAE 55-2004 standard allows elevated air speed to be used to increase the maximum temperature for acceptability if the affected occupants are able to control the air speed. The amount that the temperature may be increased is shown in Fig7.10. The combination of air speed and temperature defined by the lines in this figure results in the same heat loss from the skin. The reference point for these curves is the upper temperature limit of the comfort zone (PMV = +0.5) and 0.20 m/s (40 fpm) of air speed [ASHRAE 55-2004].

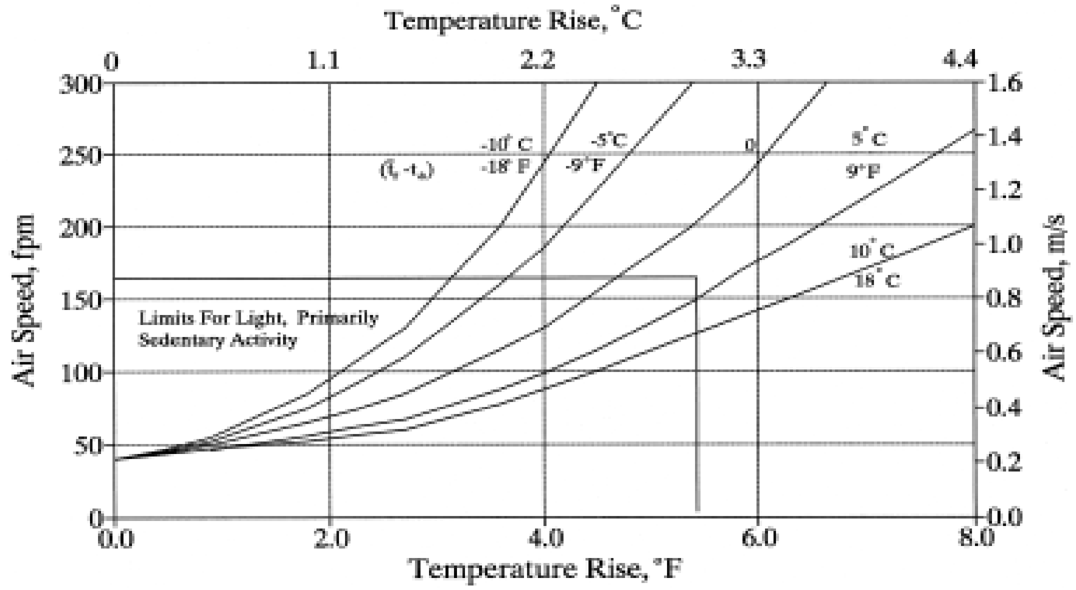


Fig 7.10 Air speed required offset increased temperature [ASHRAE 55-2004]

Elevated air speed may be used to offset an increase in the air temperature and the mean radiant temperature, but not by more than 3.0°C (5.4°F) above the values for the comfort zone without elevated air speed. The required air speed may not be higher than 0.8 m/s (160 fpm). Large individual differences exist between people with regard to the preferred air speed. Therefore, the elevated air speed must be under the direct control of the affected occupants and adjustable in steps no greater than 0.15 m/s (30 fpm). The benefits that can be gained by increasing air speed depend on clothing and activity [ASHRAE 55-2004].

7.3.2 Performance analysis of PV cooling system with modified size

In this section performance analysis of PV cooling system using modified size are presented and discussed.

Solar Fraction

Fig7.10 shows the variation of annual solar fraction with the PV area for the four different climates. It has been observed from the graph that the solar fraction is highest for the moderate climate (Bangalore) and lowest for the warm and humid climate (Chennai). Fig7.11 shows the comparison of solar fraction using 10 TR (Moderate climate -7TR) and 7TR (Moderate climate -5 TR) air conditioner. It has been observed from the graph that the solar fraction is very high when we are using the small size of air conditioner. This is due to fact that the small size air conditioners consume less power than the bigger one resulting in the good matching with the power generation by the photovoltaic panels. The solar fraction reaches as high as 0.79 for hot and dry climate (Ahmedabad), 0.89 for moderate climate (Bangalore), 0.77 for warm and humid climate (Chennai), and 0.77 for composite climate (Delhi) when 110 m^2 PV area was used.

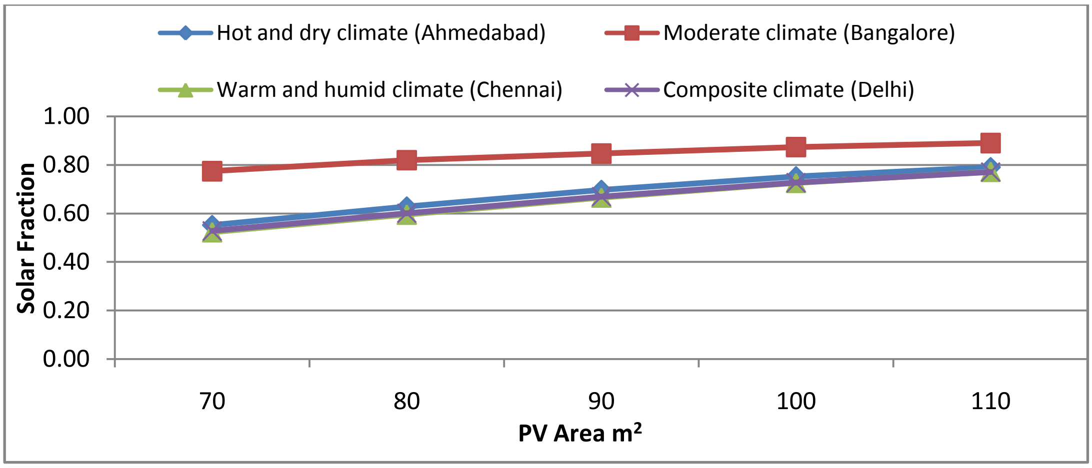


Fig .7.11 Variation of Solar Fraction with PV area

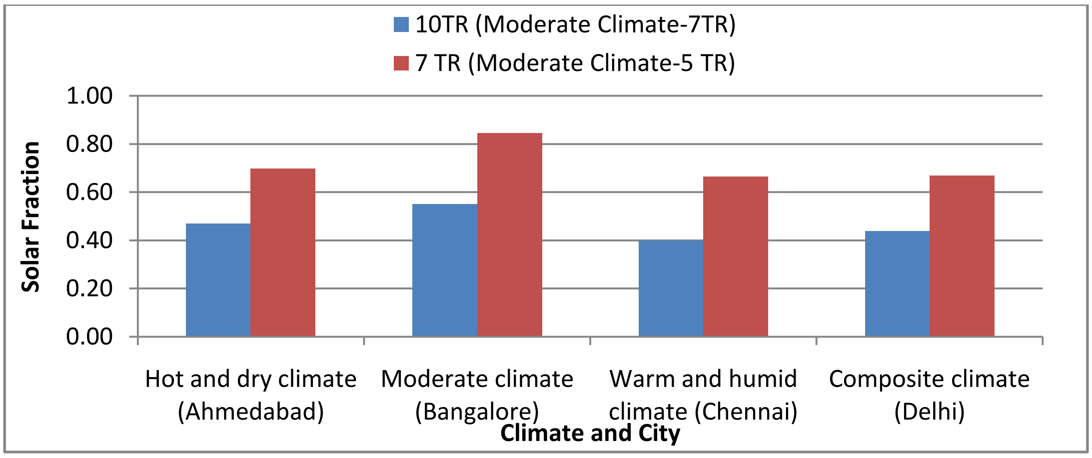


Fig 7.12 Comparison of Solar Fraction (PVArea-90 m^2)

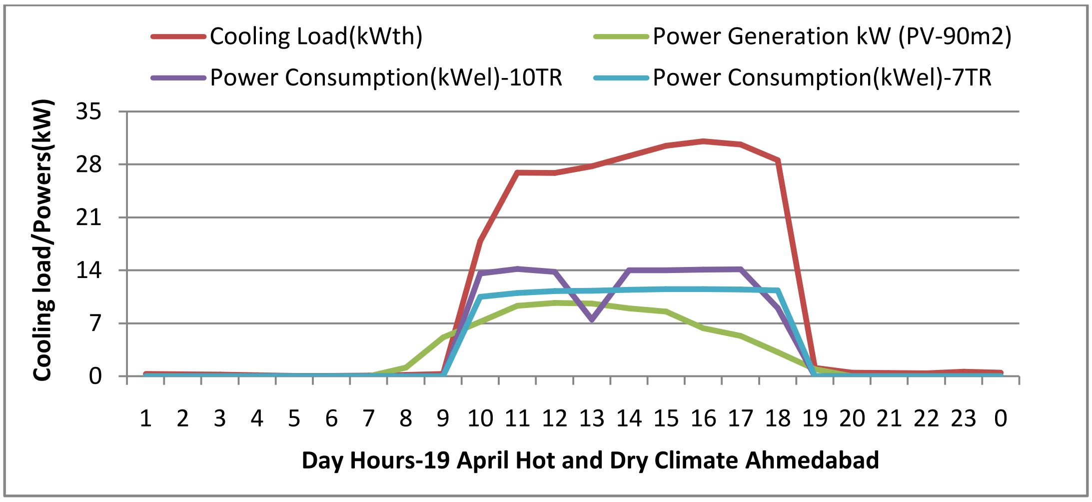


Fig: 7.13 Day Night profile of Cooling Load, Power Generation, and Consumption

Fig.7.13 shows the day night profile of cooling load, power generation, power consumption (10 TR) and power consumption (7TR) for the 19 April, Hot and dry climate Ahmedabad. On 19th April peak cooling load was reached. It has been observed from the graph that the power consumption by the bigger size air conditioner is high in comparison to the smaller one but it will off by thermostat when the temperature of building is reach the predefined temperature for comfort. While in the smaller size the compressor of the air conditioner is continuously running consuming the power but less than previous one. So in the latter case (smaller size air conditioner) there is very good matching between the power generation by the photovoltaic and power consumption resulting in the very high solar fraction. Fig 7.14 shows the temperature profile of the east, west, north south and core zone for the same day selected day of 19 April. It has been observed that the 10 TR air conditioner attain the inside temperature of building around 24˚C. In the 7 TR air conditioner the temperature of the building does not attain 24˚C and thermostat does not let the compressor to stop resulting in the continuous functioning of the compressor. This result in slightly higher electricity consumption (kWh) of the small air conditioner in comparison to the bigger but the matching between power generation and consumption is very good that possesses the high solar fraction.

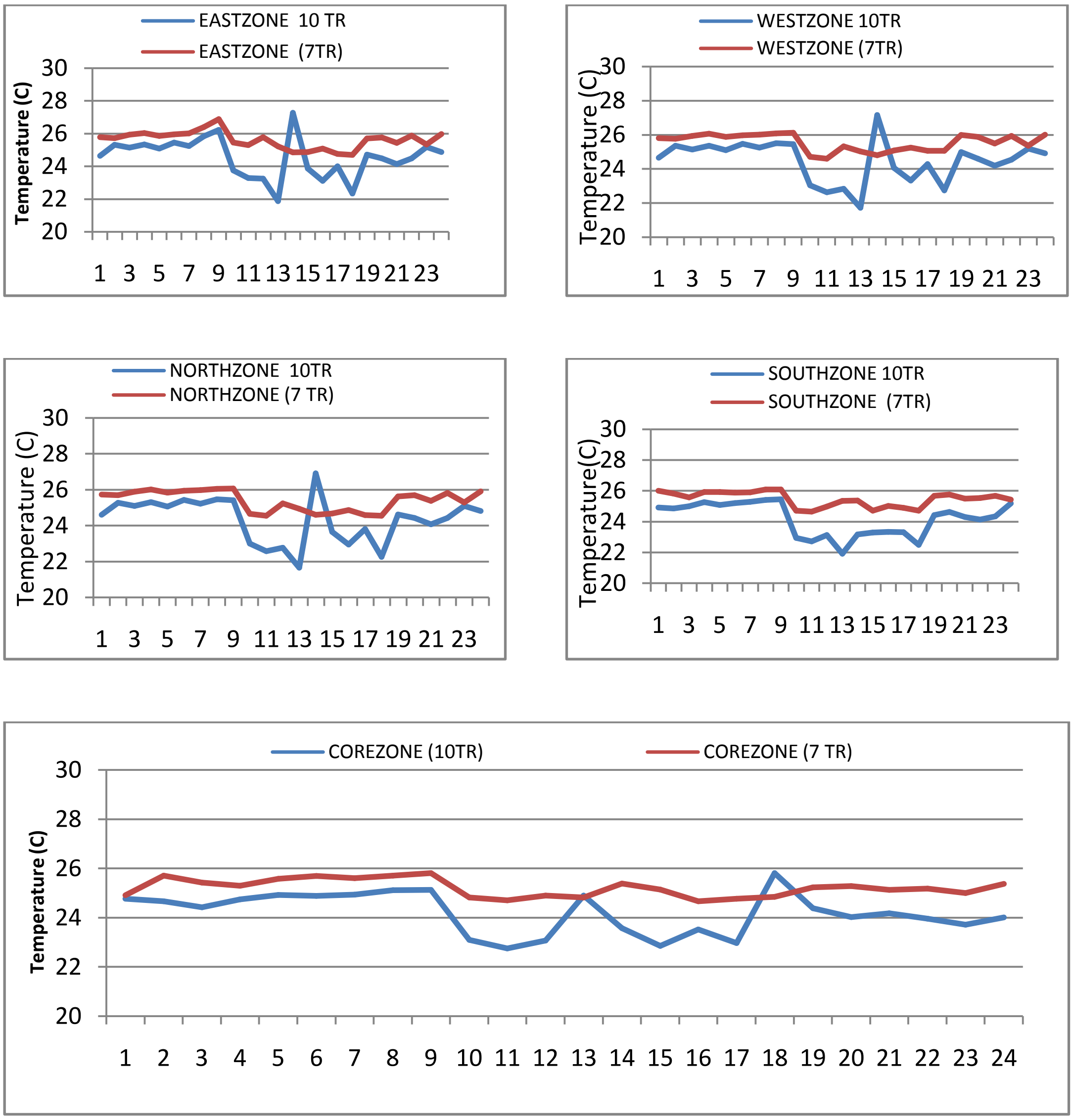


Fig: 7.14 Day Night profile of Temperature on 19 April (Hot and dry climate Ahmedabad)

However smaller air conditioner attain the temperature near about 25˚C that was within the comfort zone but in some case when it will higher than 27˚C the comfort can be achieved by the ceiling fans. The total no. of hours in a year when the temperature of the building was above 27˚C is very less. Using small size of air conditioner the unmet hours in the hot and dry climate (Ahmedabad) is 74, in moderate climate (Bangalore) 0, in warm and humid climate (Chennai) 62 , and in composite climate(Delhi) is 223. The highest temperature during office hours is 29.5 ˚C is recorded in composite climate (Delhi); in that case the comfort inside the building can be achieved by the air velocity of 0.7 m/sec.

Electrical COPs

Fig.7.15 shows the comparison of electrical COPs of 10TR and 7TR air conditioner. It has been observed from the graph that the electrical COP is very high in the 7 TR (Moderate 5 TR) because in this the solar fraction is very high resulting in the less grid power consumption.

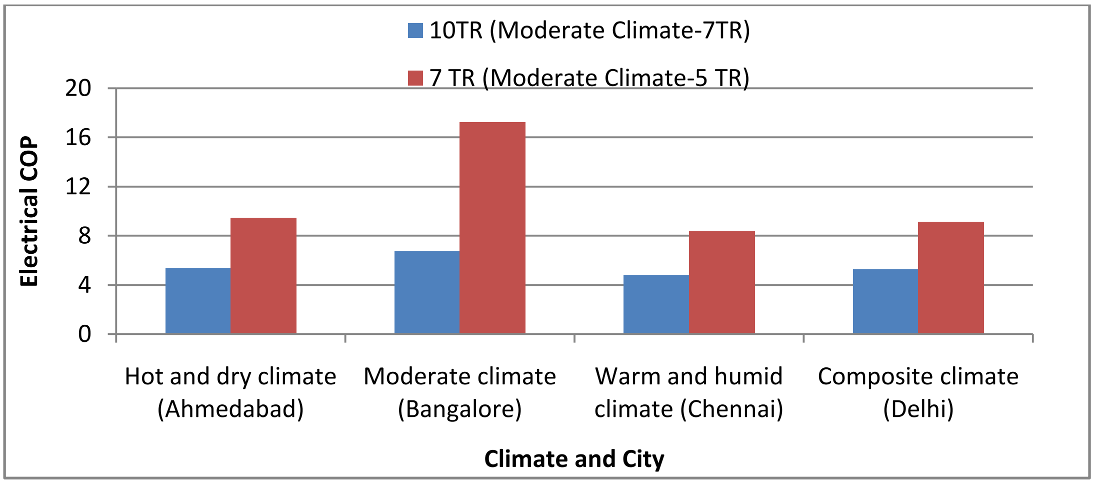


Fig 7.15 Comparison of Electrical COP (PV area-90m^2)

Payback Time:

Fig.7.16 shows the comparison of Payback time for the 10TR and 7TR air conditioner. It has been observed from the graph that the payback time is very low in the 7 TR (Moderate 5 TR) because in this the solar fraction is very high resulting in the less grid power consumption and more amount of annual savings. The payback comes down from 18 year to 11 year for the hot and dry climate (Ahmedabad), for moderate climate (Bangalore) its changes from 26 to 13 year, for moderate climate (Bangalore) its changes from 18 to 10 year for moderate climate (Bangalore) its changes from 26 to 16 year.

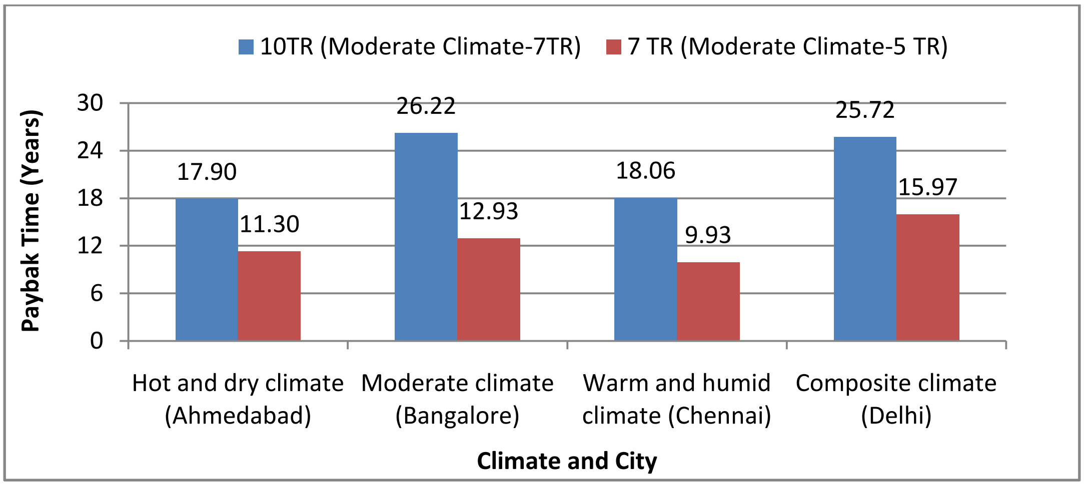


Fig 7.16 Payback Time (PV area -90m^2)

7.4 Variable Refrigerant Flow (VRF)

Reducing energy use by HVAC systems is a key strategy to energy savings and reduction of carbon emissions in buildings. VRF systems present a potential opportunity for such energy savings. VRF systems can vary refrigerant flow to meet zonal cooling and heating loads, which leads to high efficient operations during part-load conditions, and have minimal or no ductwork, which may reduce heat losses [Liu 2010]. In addition to energy benefits, VRF systems have smaller indoor fans that significantly reduce indoor noise. A typical VRF system has one outdoor unit serving multiple indoor units. Each indoor unit can have its own thermostat to control its operation [Hong T 2014].

Thus in order to decrease the energy consumption of cooling system it is proposed that the Packaged Terminal Air conditioning [PTAC] system must be replaced by the VRF. If the power consumption is reduced by using the VRF while the power generation remains same as in the case of PTAC than the solar fraction will be increased. But in the TRNSYS software it is not possible to model the VRF system for that i also email to software developer but they said that it is under development and not released publically. So it is necessary to model the VRF system on software like E-Quest, EnergyPlus. In this study we use the EnergyPlus software to model the VRF.

7.4.1 VRF System Modelling

A VRF system is a refrigerant system that varies the refrigerant flow rate with the help of a variable speed compressor and electronic expansion valves (EEVs) located in each indoor unit to match the space cooling or heating load in order to maintain the zone air temperature at the indoor set temperature. In cooling mode, the outdoor unit heat exchanger acts as condenser through the four-way valve, while the indoor unit heat exchanger acts as evaporator. The discharged refrigerant from the compressor flows into the outdoor unit, releases heat, and becomes high-pressure low temperature refrigerant. It is then throttled to low pressure by the EEV, absorbing heat from the indoor air through the indoor unit and superheating. Finally, the superheated refrigerant returns back to the compressors. In heating mode, the four-way valve reverses the refrigerant path and turns the outdoor unit into evaporator and the indoor unit into condenser. Thus the indoor unit rejects heat to the indoor air and heats it up [Hong T 2014].

The main advantages of a VRF system over the conventional multi-split system are wide-range capacity modulation, individual room set point control, and—for the heat recovery type VRF systems—the simultaneous cooling and heating capability [Goetzler W 2007], which collectively lead to better energy performance and indoor comfort. The VRF systems are residential systems that operate either in cooling mode or heating mode but not simultaneous cooling and heating. Small VRF systems have one compressor, while large systems typically include two to three compressors with fitted for variable speed capability, thus enabling wide capacity modulation. The inverter yields high part-load efficiency because HVAC systems often operate in the range 40% to 80% of its maximum capacity, while the single speed units have to cycle on and off causing efficiency losses. Heat recovery is readily accomplished when simultaneous heating and cooling occurs, which leads to energy savings. The inverter technology used in the VRF system can maintain precise room temperature control, generally within ±0.55°C (±1°F) [Hong T 2014].

EnergyPlus version 8.1 can model the heat pump type and heat recovery type VRF systems. The object AirConditioner: VariableRefrigerantFlow describes the outdoor unit which connects to the zone terminal units (indoor units). Zone terminal units operate to meet the zone sensible cooling or heating requirements as determined by the zone thermostat schedule. The actual operation mode is determined based on the master thermostat priority control type. There are five algorithms available: LoadPriority, ZonePriority, ThermostatOffsetPriority, MasterThermostatPriority, and Scheduled. LoadPriority uses the total zone load to choose the operation mode as either cooling or heating. ZonePriority uses the number of zones requiring cooling or heating to determine the operation mode. ThermostatOffsetPriority uses the zone farthest from the room set point to determine the operation mode. The MasterThermostatPriority operates the system according to the zone load where the master thermostat is located. Scheduled operates the VRF system either in cooling or heating based on schedule. When the system is running in cooling mode, the cooling coils will be enabled only in the terminal units where cooling is required. In heating mode, the heating coils only response to the zones with heating load. The indoor unit supply fan can be modeled in two operation modes: cycling fan cycling coil (AUTO fan mode) or continuous fan cycling coil (Fan ON mode). To model the AUTO fan mode, only the Fan: OnOff object can be used. For the Fan ON mode, both Fan: OnOff and Fan: ConstantVolume objects can be used [Hong T 2014].

Model validation

The whole building modeling was done in the energy plus software with the same building parameter and HVAC systems. Fig 7.17 shows the variation of cooling load for a day time calculated by the two software TRNSYS and Energy plus. It is clear from the graph that the cooling load is nearly same.

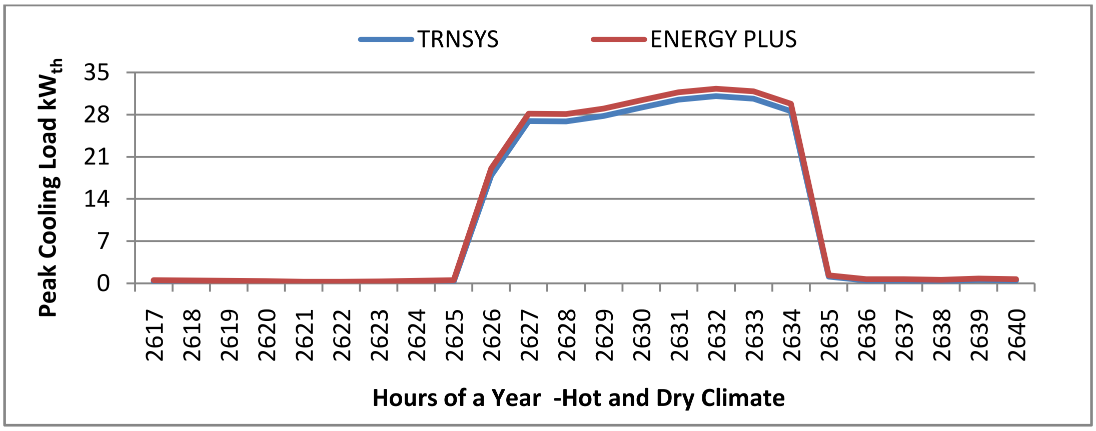


Fig: 7.17 Comparsion of Cooling Load [Hot and dry climate -Ahemedabad]

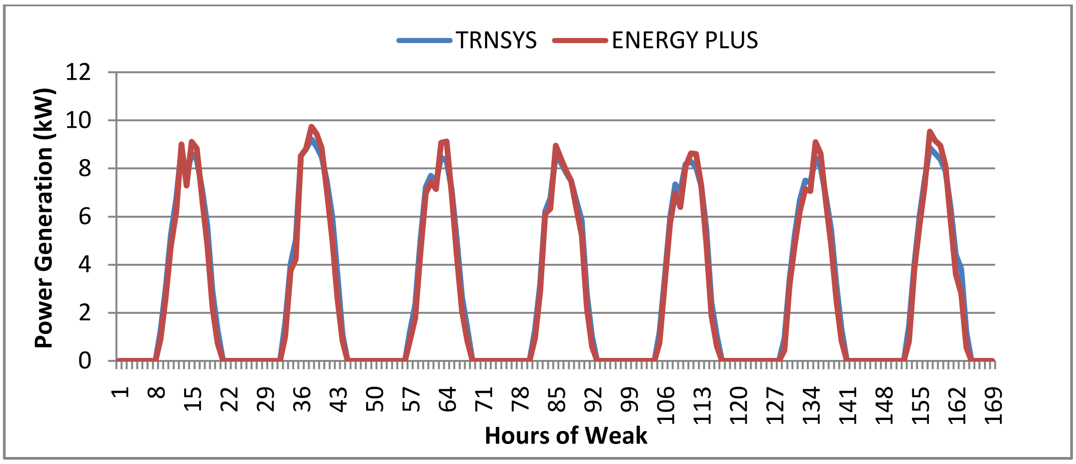


Fig: 7.18 Comparsion of Power Generation [70 m^2 PV Area Mono crystalline]

Fig 7.18 shows the comparison of power generation by the two softwares TRNSYS and ENERGY PLUS. It has been observed from the graph that the power generation is approximately same in ENERGY PLUS as in TRNSYS.

7.4.2 Performance analysis of PV cooling system with VRF

In this section performance analysis of PV cooling system using variable refrigerant flow presented and discussed.

Solar Fraction

The Power consumption of the VRF cooling system decreases in comparison to the PTAC system while the power generation from the photovoltaic remains the same. So in the day time there is good matching between the PV generation and the energy consumption of the VRF system that enhances the solar fraction.

Fig 7.19 (a) shows the variation of solar fraction with PV area. It has been observed from the fig.7.19 that the highest solar fraction is achieved for the moderate climate Bangalore because of low cooling demand resulting in low electrical energy consumption of the VRF system. In the moderate climate power generation from the photovoltaic system is good and energy consumption by air conditioner is low so there is a good matching of power generation and consumption in the day time that enhances the solar fraction. The lowest solar fraction is for warm and humid climate (Chennai) because of the highest annual cooling demand. Using VRF technology the solar fraction reaches upto 0.89 for hot and dry climate

(Ahmedabad), 0.95 for moderate climate (Bangalore), 0.84 for warm and humid climate (Chennai) and 0.88 for composite climate (Delhi). Fig.7.19 (b) shows the comparison of solar fraction for the PTAC and VRF system. The solar fraction is higher for VRF technology.

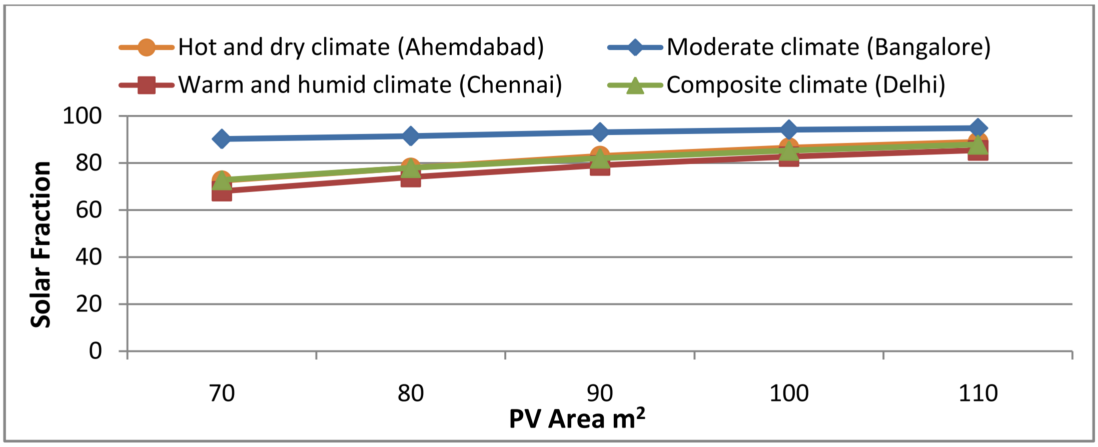


Fig: 7.19 (a) Variation of Solar Fraction with PV area

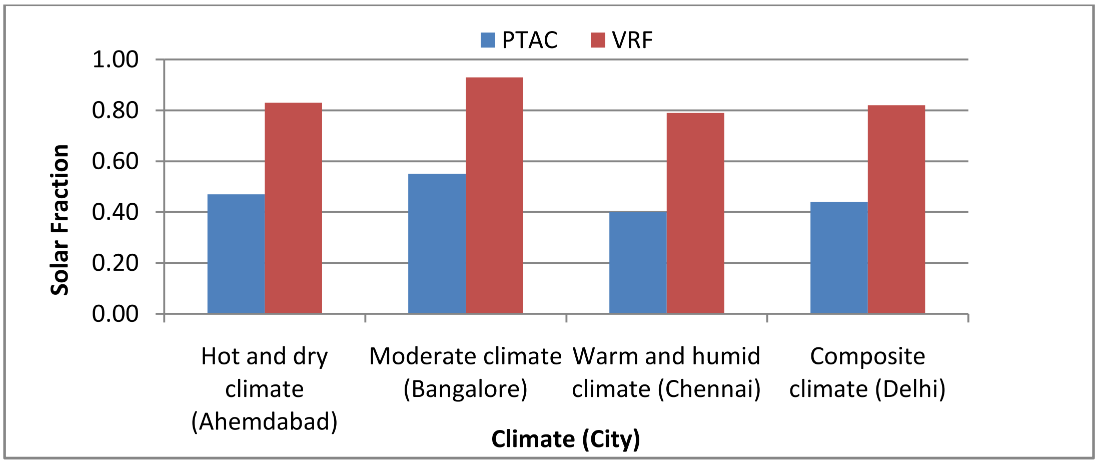


Fig: 7.19 (b) Comparsion Solar Fraction (PV area-90m^2)

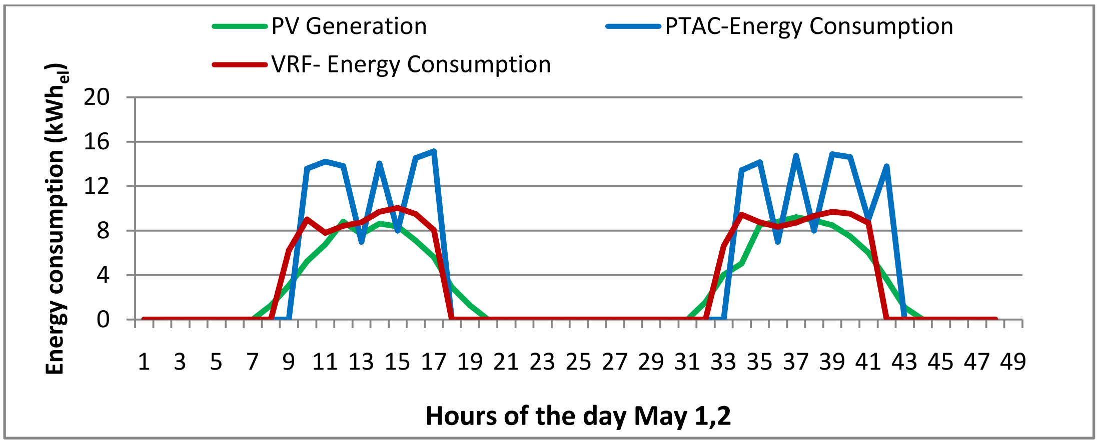


Fig: 7.20 Comparison of PV generation and consumption [Hot and dry climate (Ahemdabad) PV area 90 m^2]

Fig 7.20 shows the comparison of energy consumption and PV generation for hot and dry climate (Ahemdabad). It has been observed from the graph that the PTAC consumption is very high in comparison to the PV generation. The difference between the two is taken by grid supply that is the reason why the solar fraction is lower in the PTAC system. The consumption of the VRF system follows the same trends as the generation of PV power so only a small amount of grid supply is required resulting in the high solar fraction. In the PTAC system there is condition in the day time when the thermostat OFF the compressor in that case the PV generates power but consumption is zero and solar fraction is not calculated.

Although using VRF system the solar fraction achieved is very high in comparison to the conventional system but the total energy consumption is reduced 11-28%. Fig 7.21 shows the comparison of annual electrical energy consumption for the four different climates with the VRF and conventional PTAC system.

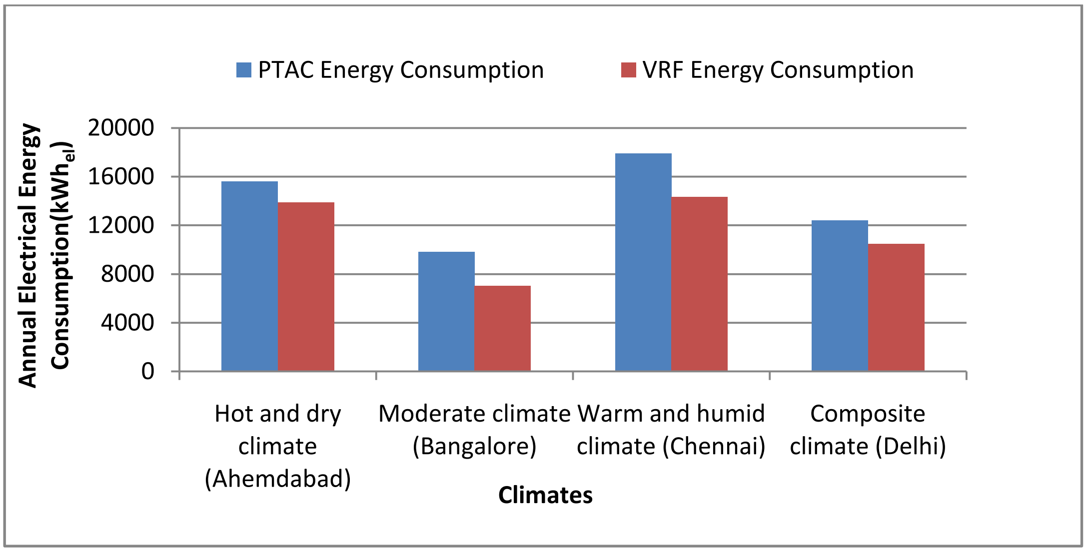


Fig: 7.21 Comparison of annual electrical energy consumption

It has been observed from the graph that the saving in the annual electrical energy consumption is very high 28% for moderate climates because the cooling demand of moderate climates is low in comparison to the other one. The low cooling demand decreases the size and electrical energy consumption of the cooling system. In the hot and dry climate (Ahemdabad) and composite climates (Delhi) the peak cooling load are highest during summer season so the both systems (PTAC and VRF) consume the electrical energy at almost same level. In the warm and humid climate the cooling load remains same throughout the year so in this condition the VRF system can save the electrical energy consumptions.

Electrical COPs

Fig 7.22 shows the variation of electrical COPs for the four different climates having the two options that is PTAC and VRF. It has been observed from the fig that the Electrical COPs are very high for VRF system because in this system the annual solar fraction is very high resulting in the very low consumption of grid power that enhances the electrical COP. Moderate climate has the highest electrical COP because of the low cooling demand.

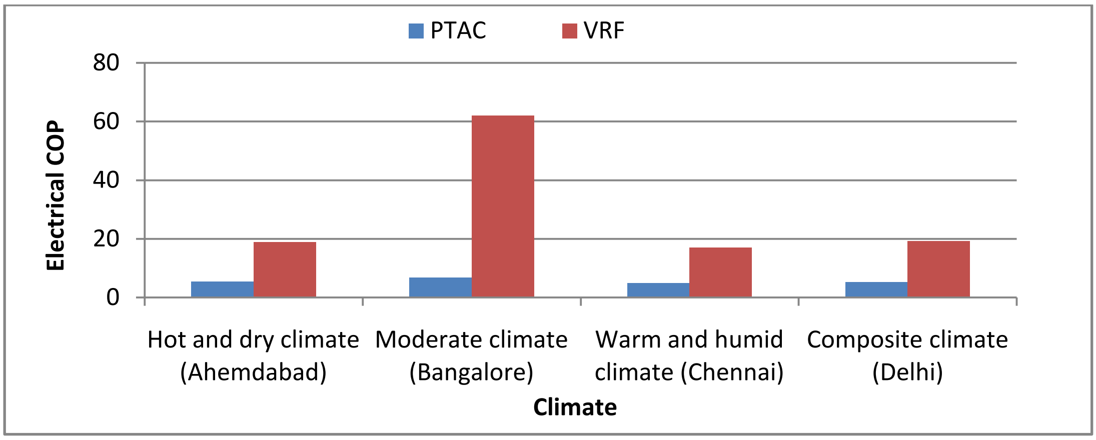


Fig 7.22 Comparison of Electrical COP [PV area-90 m^2]

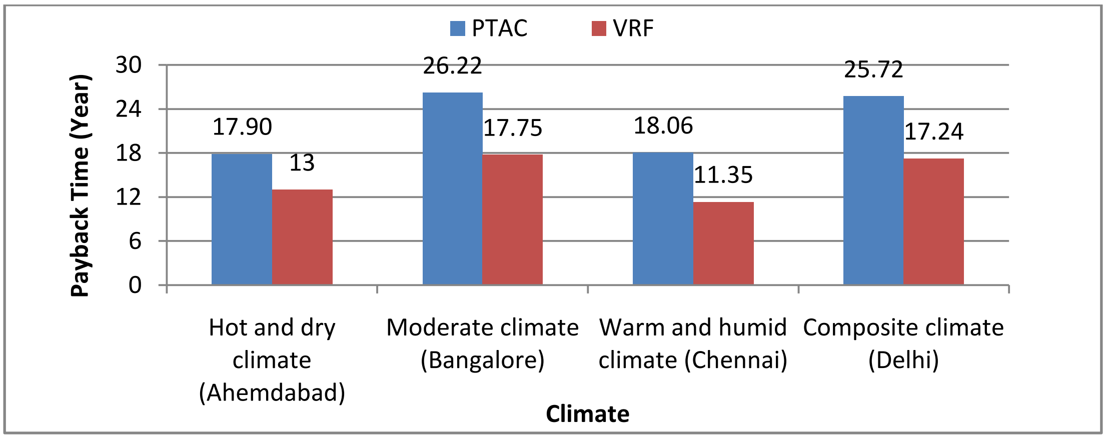


Fig 7.23 Comparison of payback time COP [PV area-90 m^2]

Payback Time

Fig 7.23 shows the variation of Payback time for the four different climates having the two options that is PTAC and VRF. It has been observed from the fig 7.22 that the payback time is less for VRF system because in this system the annual solar fraction is very high resulting in the very low consumption of grid power. The payback time comes down to 18 year to 13 year for hot and dry climate, 26 to 18 year for the moderate climate, 18 year to 11 years for the warm and humid climate and 26 to 17 year for composite climate. In future payback may down as the cost of VRF system decreases.The present cost of VRF is 1.6 times than non VRF system [Climatech Aircon Engineering Pvt. Ltd. Jaipur 2014].

7.5 Summary of Chapter

In this chapter, various techniques were evaluated for performance enhancement of PV cooling systems like tracking, thermal mass, modifying air conditioner sizing approach and use of VRF technology. Tracking of PV panels increased solar fraction in the range of 5-9% in all the considered climates; and the payback period is very high due to high cost of trackers. Thermal mass does not provide significant effect on solar fraction. Modifying the air conditioner size by reducing the capacity from 10 TR to 7 TR, improved the solar fraction with reduction in the payback time. The solar fraction reaches as high as 0.79 for hot and dry climate (Ahmedabad), 0.89 for moderate climate (Bangalore), 0.77 for warm and humid climate (Chennai), and 0.77 for composite climate (Delhi). By using this system the payback time would come down to 11, 13, 10, and 16 year for hot and dry, moderate, warm and humid and composite climate respectively. It is lowest for the warm and humid climate because of highest annual cooling demand with improved solar fraction. Use of VRF technology enhances the solar fraction along with the reduction in the energy consumption and payback period. The solar fraction reaches up to 0.89 for hot and dry climate (Ahmedabad), 0.95 for moderate climate (Bangalore), 0.84 for warm and humid climate (Chennai) and 0.88 for composite climate (Delhi). The payback time come down to 13, 18, 11, and 17 years for hot and dry climate, moderate climate, warm and humid climate and composite climate respectively. It is lowest for the warm and humid climate due to highest annual cooling demand and it is highest for the moderate climate because of the lowest annual cooling demand and higher cost of VRF than PTAC.

CHAPTER 8 CONCLUSION AND FUTURE WORKS

8.1 Summary of Work

This study covers the techno- economic comparison between solar energy based cooling systems using solar thermal and solar photovoltaic (PV) technology. Analysis has been carried through simulation of a typical office building considered to be located in four different cities, representing four climatic zones of India namely Hot and dry, Warm and humid, Moderate, and Composite. The fifth climatic zone of the country i.e. Cold and cloudy has not been considered due to very less and practically insufficient cooling demand as compared to other four. For both the cooling technologies multiple options have been considered; flat plate, evacuated and compound parabolic collector for solar thermal and mono crystalline, poly crystalline and thin film for PV. A single effect lithium-bromide vapour absorption chiller has been considered for producing cooling effect in the solar thermal route, where as vapour compression cycle based cooling system is modeled for the solar photovoltaic cooling system. For a comparative analysis, the building geometry, user profile and construction have been considered identical for chosen locations in four climatic zones; Ahmedabad from hot and dry zone, Bangalore from moderate zone , Chennai from warm and humid zone and Delhi from composite zone. Energy simulation of building and coupled solar cooling system has been carried using TRNSYS v-17 software. Iterations were carried out for different technology versions and with a wide variance of collector area for the solar thermal cooling system. Based on the results given by the program key parameters, solar fraction, and primary energy savings, electrical (Grid) COP and payback period are calculated for both types of cooling systems. Finally technical and financial comparison is made for the two technologies. In the last in order to increase the solar fraction of the PV cooling system various techniques were analysed using tracking, thermal mass, modifying sizing approach for air conditioner and use of VRF technology.

8.2 Technical Feasibility

Technical feasibility of solar thermal and solar photovoltaic cooling system is evaluated based on the basis of solar fraction and primary energy savings.

8.2.1 Solar fraction

Solar thermal cooling system

- The solar fraction is highest for the moderate climate (Bangalore) and lowest for the warm and humid climate (Chennai) because the cooling demand of the building is 131 kWh_{th}/m^2 in the moderate climate is 42% less than the warm and humid climate while the solar radiation is 2094 kWh/m^2 in the moderate climate that is 2% more than the warm and humid climate.
- The solar fraction is highest for the CPC type collector and lowest for the FPC. In both type, ETC and CPC, out of the four climate the solar fraction is highest for the moderate climate and lowest for the warm and humid climate similar as in the FPC type.
- It has been observed that for flat plate collectors the highest solar fraction occurs at 110 m^2 collector area in all considered climatic zones, in the case of ETC highest solar fraction is at collector area of 100 m^2 in the hot and dry climate (Ahmedabad), warm and humid climate (Chennai) and composite climate (Delhi) where as it is 90 m^2 for moderate climate (Bangalore). In the Bangalore city the cooling demand of the building is quite low in comparison to other cities so 90 m^2 collector area offers highest solar fraction beyond this collector area, more collector losses and result into decrease in the solar fraction. In the case of CPC highest solar fraction occurs in the hot and dry (Ahmedabad) and warm and humid climate (Chennai) at 90m^2 collector area, for moderate (Bangalore) it is 70m^2 and for composite climate (Delhi) it is 100 m^2.
- In the solar thermal cooling system as the collector area increases the solar fraction also gets increased but after an optimum collector area it starts decreasing because at elevated temperature heat losses are also higher. If we use a high collector area then we have to increase either the capacity of storage tank or the cooling demand of the building otherwise there will be no effect of collector area after an optimum value. The highest solar fraction has been observed as 0.89, 0.94, 0.88, and 0.93 for hot and dry, moderate, warm and humid and composite climate respectively.

Solar photovoltaic cooling system

(a) Use of non VRF compressor

- The highest solar fraction (0.46-0.60) for mono crystalline -cells is observed for the moderate climate due to lowest cooling demand resulting in lowest power consumption but the annual power generation by PV is moderate. The lowest solar fraction (0.32-0.49) for mono-cells is observed in the warm and humid climate due to very high cooling load 225 kWh_{th}/m^2 and high annual power consumption of 17912 kWh_{el}.
- For hot and dry and composite climate the annual solar fraction ranges between 0.34-0.57, and 0.35-0.54 respectively. The value of solar fraction for the composite climate is also higher because of the good matching between the power generation and the cooling demand in the summer months.
- The annual solar fraction is lower for the thin film cells because of the low efficiency of cells for all type of climates. The annual power generation for the poly cell is higher than the thin film but lower than the mono-cell so the annual solar fraction for poly-cell lies between the mono and thin film cells.

(b) Use of VRF, Modified sizing approach, Tracking system and Thermal mass

- By use of VRF technology solar fraction reaches up to 0.89 for hot and dry climate (Ahmedabad), 0.95 for moderate climate (Bangalore), 0.84 for warm and humid climate (Chennai) and 0.88 for composite climate (Delhi).
- Modifying sizing approach of air conditioner by reducing the capacity from 10 TR to 7 TR, improved the solar fraction. The solar fraction reaches as high as 0.79 for hot and dry climate (Ahmedabad), 0.89 for moderate climate (Bangalore), 0.77 for warm and humid climate (Chennai), and 0.77 for composite climate (Delhi).
- Tracking of PV panels increase the solar fraction in the range of 5-9%.
- Use of thermal mass in building envelope was not found to have significant impact on solar fraction.

Comparison of solar thermal and solar photovoltaic cooling system

- Solar Fraction (S.F) is higher for solar thermal cooling than the solar photovoltaic cooling system (non VRF compressor) of any particular collector area in all the climates. Because in the thermal cooling system there is a storage device (hot storage tank) between the solar thermal collector and cooling machine resulting in continuous operation of vapour absorption machine without using the grid power for small fluctuation in solar radiations. In the solar photovoltaic cooling system (grid supported) the annual solar fraction is calculated without considering the storage device. The vapour compression machine (Packaged air conditioner) requires a fix amount of power to drive the compressor, if instantaneously it is available on PV it is supplied to the cooling system otherwise it is taken from the grid and not accounted for the annual solar fraction.
- With increase in the collector area the solar fraction increases rapidly for solar photovoltaic cooling system than the solar thermal cooling system because in the solar photovoltaic cooling system any increase in area directly increase power output and supplied to the system. While in the solar thermal cooling system increase in the collector area, losses are also increased resulting in the slow increment in solar fraction. After a certain optimum area solar fraction will constant or even decreases.
- Use of VRF and modified sizing approach enhances the solar fraction to the range of 0.84 to 0.95 and 0.77 to 0.89 respectively. Making it comparable with the solar fraction of solar thermal cooling system.

8.2.2 Primary energy savings

Solar thermal cooling system

- In the solar thermal cooling system the highest primary energy savings are highest for the moderate climate (Bangalore) 55-62 % and lowest for the warm and humid climate (Chennai) 44-55%. It is between 54- 62 % for the hot and dry climate (Ahmedabad) and 51 - 61 % for the composite climate (Delhi). The primary energy savings are highest for moderate climate due to very low cooling demand of 131 kWh_{th}/m^2 and the primary energy savings are lowest for the warm and humid climate (Chennai) because of the very high cooling demand of 225 kWh_{th}/m^2.

- Among the three types of collectors CPC has the higher primary energy savings.
- At high collector area the collected heat is increased in all the type of collector but in the case of ETC and CPC the heat losses also increase, so with the increase in the collector area the increment in the primary energy savings are higher for the FPC and lower for the ETC and CPC. In the ETC and CPC after an optimum collector area the primary energy savings gets decreased. For the same cooling machine type, capacity and building cooling load increase in collector area does not produce much effect in case of primary energy savings. The highest primary energy savings is 71.05% for hot and dry climate (Ahmedabad), 73.74% for moderate climate (Bangalore), 65.86% for warm and humid (Chennai) and 71.70% for the composite climate (Delhi).

Solar photovoltaic cooling system

(a) Use of non VRF compressor

- The highest primary energy saving are for the mono crystalline cell and lowest for the thin film cells, and for poly crystalline cells it is between mono crystalline and thin film because for same installed PV are the annual power generation is high for mono-cell.
- The primary energy savings are highest 44%-60% for the moderate climate and lowest for the warm and humid climate, the reason is same as in the annual solar fraction.

(b) Use of VRF, Modified sizing approach, Tracking system and Thermal mass

- By use of VRF and modified sizing approach enhances the primary energy saving. It reaches in the range of 84%-95% and 77% to 89% for VRF and modified size respectively.

On the basis of solar fraction, both the cooling systems are technically feasible since they offer solar fraction greater than 0.50. The solar fraction for solar thermal cooling system is ranging between0.51 to 0.94. In case of solar photovoltaic cooling system use of VRF technology and modified sizing approach offeres solar fraction in the range of 0.77 to 0.95. It is also observed that with non VRF compressor and with use of conventional method of AC system sizing, the solar fraction of PV route is lower than 0.50 in many cases. This puts a question on even financial feasibility of such solar cooling system.

8.3 Financial Feasibility

Financial feasibility of solar thermal and solar photovoltaic cooling system is evaluated based on the payback periods and IRR calculations.

- With the present cost structure solar thermal cooling system is not financially feasible in any climatic condition of India due to high initial cost of vapour absorption chiller, and solar collector, that result in very high payback periods (65-242 years). Practically meaning no payback period since it is more than product life. The high initial cost is also linked with high maintenance cost, where as it provides only marginal annual savings. The highest payback period is in the moderate climate due to the low cooling demand of the building resulting into low utilization of system. Lowest payback period is for the warm and humid climate due to larger amount of cooling requirement and high utilization of system on annual basis. However this type of systems may be feasible in the areas where the grid electricity is not available and local generation of electricity is too costly.
- Similar to solar thermal systems, solar photovoltaic cooling system (using PTAC) also has a high payback period, however it is significantly lower than solar thermal systems. Lowest payback period of 14.23 years is found for hot and dry climate (Ahmedabad) due to good combination of cooling demand and annual electricity generation, where as for moderate climate (Bangalore) payback period is highest 26 years.
- By use of VRF technology the payback time comes down to 13, 18, 11, and 17 years for hot and dry climate, moderate climate, warm and humid climate and composite climate respectively. It is lowest for the warm and humid climate and highest for the moderate climate.

- By using the modified sizing approach for air conditioner the payback time would come down to 11, 13, 10, and 16 year for hot and dry, moderate, warm and humid and composite climate respectively.
- By using the tracking of PV panels increase the payback period is increase due to high cost of tracking system.
- When PV based systems are optimally used with net metering provisions during the non cooling periods then the payback period is 4-6 years for all climatically zones.

On the basis of this study it is concluded that out of various contemporary options considered, solar PV based cooling system using VRF compressor, modifying sizing approach looks most promisimg options. Availability of net metering system in electricity billing may further enhance possibility of adoption of solar cooling system.

8.5 Scope of Future Work

Although it has tried to cover the analysis of solar thermal cooling system and solar photovoltaic cooling system as much as possible and comparison is made, still there is always scope for future work in research field. The future scope related to present work is as:

- Analysis can be carried out for the solar thermal cooling system using double/triple effect vapour absorption chillers especially with the ETC and CPC.
- Simulation can be carried out for the solar photovoltaic cooling system using variable frequency drive compressor with thermal mass and tracking system.
- Analysis can be carried out for combined application of cooling, heating, and domestic hot water production.
- Analysis can be done using different configuration of cooling systems for different climates.
- Analysis can also be done for adsorption based and desiccant cooling systems.
- Analysis can be carried out for standalone solar photovoltaic cooling systems.

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Appendix: A1-12 Solar Thermal Cooling System - Energy and cost performance sheet

A-1 Hot and dry climate (Ahmedabad) – FPC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	156041	176846	197651	218456	244039	
3	Solar heat production	kWh	36212	40220	43510	46419	49586	
4	Solar heat contribution -cooling	kWh	33397	37399	40680	43578	46735	
5	Total cooling energy demand	kWh	44574	44595	44607	44613	44619	
6	Solar cooling produced by absorption chiller	kWh	26490	29073	30723	31990	33345	
7	Auxiliary cooling-back up chiller	kWh	18084	15522	13884	12623	11274	
8	Net collector efficiency	%	0.23	0.23	0.22	0.21	0.20	
9	Solar fraction	Unit less	0.59	0.65	0.69	0.72	0.75	
10	Annual incident radiation per unit collector area	kWh/m^2	2176	2176	2176	2176	2173	
11	Specific useful net collector output	kWh/m2	505	495	479	462	441	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	5167	4435	3967	3607	3221	
13	Annual power consumption by pumps	kWh_{el}	2012	2258	2442	2571	2645	
14	Total annual tower consumption	kWh_{el}	7179	6693	6409	6178	5866	
15	Electrical COP absorption chiller	Unit less	10.15	9.95	9.74	9.61	9.68	
16	Cooling tower power consumption	kWh_{el}	598.87	664.72	714.03	755.68	800.80	
17	Electrical COP system	Unit less	5.73	6.06	6.26	6.43	6.69	
18	Electrical consumption -reference	kWh_{el}						15618
19	Annual primary energy consumption - Reference	kWh_{PE}						43383
20	Annual primary energy consumption -thermal	kWh_{PE}	19941	18592	17802	17161	16296	
21	Relative primary energy savings	kWh_{PE}	23442	24791	25581	26222	27088	
22	Relative primary energy saving %	%	54.03	57.14	58.97	60.44	62.44	
23	Specific primary energy savings	kWh_{PE}/m^2	326.95	305.08	281.67	261.23	241.14	
24	Total Investment Cost	INR	3179600	3242100	3304600	3367100	3429600	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	324319	330694	337069	343444	349819	87000
27	Maintenance cost	INR	43507	44132	44757	45382	46007	7500
28	Annual electricity cost	INR	54200	50534	48386	46644	44291	117916
29	Total annual cost	INR	422026	425359	430212	435470	440117	212416
30	Annual operation and maintenance cost	INR	97707	94665	93142	92026	90298	125416
31	Annual extra cost of solar system	INR	209610	212943	217796	223054	227701	
32	Cost of saved primary energy	INR/kWh	8.94	8.59	8.51	8.51	8.41	
33	Payback time	Years	96.70	89.17	86.90	85.87	83.42	

A-2 Hot and dry climate (Ahmedabad) – ETC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	156544	176111	195678	220138	239214	
3	Solar heat production	kWh	52397	55037	57692	59005	59487	
4	Solar heat contribution -cooling	kWh	49560	52192	54839	56149	56628	
5	Total cooling energy demand	kWh	44641	44645	44652	44653	44649	
6	Solar cooling produced by absorption chiller	kWh	36392	37371	38085	38411	38243	
7	Auxiliary cooling-back up chiller	kWh	8249	7274	6567	6242	6406	
8	Net collector efficiency	%	0.33	0.31	0.29	0.27	0.25	
9	Solar fraction	Unit less	0.82	0.84	0.85	0.86	0.86	
10	Annual incident radiation per unit collector area	kWh/m^2	2174	2174	2174	2174	2170	
11	Specific useful net collector output	kWh/m2	728	679	641	583	540	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	2357	2078	1876	1783	1830	
13	Annual power consumption by pumps	kWh_{el}	2928	3127	3127	3161	3157	
14	Total annual tower consumption	kWh_{el}	5285	5205	5003	4944	4987	
15	Electrical COP absorption chiller	Unit less	9.61	9.29	9.39	9.35	9.31	
16	Cooling tower power consumption	kWh_{el}	859.52	895.63	929.24	945.6	948.71	
17	Electrical COP system	Unit less	7.27	7.32	7.53	7.58	7.52	
18	Electrical consumption -reference	kWh_{el}						15618
19	Annual primary energy consumption - reference	kWh_{PE}						43383
20	Annual primary energy consumption -thermal	kWh_{PE}	14680	14459	13898	13735	13854	
21	Relative primary energy savings	kWh_{PE}	28703	28924	29485	29649	29530	
22	Relative primary energy saving %	%	66.16	66.67	67.96	68.34	68.07	
23	Specific primary energy savings	kWh_{PE}/m^2	398.66	357.09	327.61	292.83	267.84	
24	Total Investment Cost	INR	3393100	3486100	3579100	3672100	3765100	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	346096.2	355582.2	365068.2	374554.2	384040.2	87000
27	Maintenance cost	INR	45642	46572	47502	48432	49362	7500
28	Annual electricity cost	INR	39901	39300	37775	37330	37654	117916
29	Total annual cost	INR	431638	441454	450345	460316	471056	212416
30	Annual operation and maintenance cost	INR	85542	85871	85276	85762	87016	125416
31	Annual extra cost of solar system	INR	219222	229038	237929	247900	258640	
32	Cost of saved primary energy	INR/kWh	7.64	7.92	8.07	8.36	8.76	
33	Payback time	Years	72.56	75.51	76.71	79.99	85.03	

A-3 Hot and dry climate (Ahmedabad) – CPC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	151870	177181	197429	217678	242434	
3	Solar heat production	kWh	58817	58817	58817	58817	58817	
4	Solar heat contribution -cooling	kWh	49255	53071	55349	56083	57284	
5	Total cooling energy demand	kWh	44641	44650	44651	44644	44645	
6	Solar cooling produced by absorption chiller	kWh	37719	39240	39744	39695	39844	
7	Auxiliary cooling-back up chiller	kWh	6922	5410	4907	4949	4801	
8	Net collector efficiency	%	0.39	0.33	0.30	0.27	0.24	
9	Solar fraction	Unit less	0.84	0.88	0.89	0.89	0.89	
10	Annual incident radiation per unit collector area	kWh/m^2	2173	2173	2173	2173	2168	
11	Specific useful net collector output	kWh/m2	841	721	647	587	526	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	1978	1546	1402	1414	1372	
13	Annual power consumption by pumps	kWh_{el}	2828	3054	3121	3110	3172	
14	Total annual tower consumption	kWh_{el}	4806	4600	4523	4524	4544	
15	Electrical COP absorption chiller	Unit less	10.20	9.87	9.76	9.76	9.62	
16	Cooling tower power consumption	kWh_{el}	869.74	923.11	950.93	957.78	971.28	
17	Electrical COP system	Unit less	7.87	8.08	8.16	8.14	8.10	
18	Electrical consumption -reference	kWh_{el}						15618
19	Annual primary energy consumption - Reference	kWh_{PE}						43383
20	Annual primary energy consumption -thermal	kWh_{PE}	13349	12777	12564	12567	12621	
21	Relative primary energy savings	kWh_{PE}	30034	30606	30819	30817	30762	
22	Relative primary energy saving %	%	69.23	70.55	71.04	71.03	70.91	
23	Specific primary energy savings	kWh_{PE}/m^2	429.67	375.31	339.16	307.58	275.05	
24	Total Investment Cost	INR	3687100	3822100	3957100	4092100	4227100	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	376084	389854	403624	417394	431164	87000
27	Maintenance cost	INR	48582	49932	51282	52632	53982	7500
28	Annual electricity cost	INR	36283	34728	34149	34156	34305	117916
29	Total annual cost	INR	460949	474514	489054	504182	519451	212416
30	Annual operation and maintenance cost	INR	84865	84659	85430	86788	88287	125416
31	Annual extra cost of solar system	INR	248533	262098	276638	291766	307035	
32	Cost of saved primary energy	INR/kWh	8.28	8.56	8.98	9.47	9.98	
33	Payback time	Years	78.59	81.51	86.46	92.99	100.38	

A-4 Moderate climate (Bangalore) – FPC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	150156	170171	190197	210218	235244	
3	Solar heat production	kWh	28837	31322	33215	34464	35588	
4	Solar heat contribution -cooling	kWh	25617	28089	29970	31214	32339	
5	Total cooling energy demand	kWh	30014	30027	30039	30050	30059	
6	Solar cooling produced by absorption chiller	kWh	19909	21091	21890	22615	23249	
7	Auxiliary cooling-back up chiller	kWh	10105	8936	8149	7435	6810	
8	Net collector efficiency	%	0.19	0.18	0.17	0.16	0.15	
9	Solar fraction	Unit less	0.66	0.70	0.73	0.75	0.77	
10	Annual incident radiation per unit collector area	kWh/m^2	2094	2094	2094	2094	2094	
11	Specific useful net collector output	kWh/m2	402	385	366	343	317	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	2887	2553	2328	2124	1946	
13	Annual power consumption by pumps	kWh_{el}	1519	1602	1665	1722	1786	
14	Total annual tower consumption	kWh_{el}	4406	4155	3993	3846	3732	
15	Electrical COP absorption chiller	Unit less	10.08	10.07	10.02	10.01	9.93	
16	Cooling tower power consumption	kWh_{el}	455.26	491.80	518.60	538.29	555.88	
17	Electrical COP system	Unit less	6.17	6.46	6.66	6.85	7.01	
18	Electrical consumption -reference	kWh_{el}						9825
19	Annual primary energy consumption - Reference	kWh_{PE}						27292
20	Annual primary energy consumption -thermal	kWh_{PE}	12239	11542	11092	10684	10366	
21	Relative primary energy savings	kWh_{PE}	15052	15750	16199	16608	16926	
22	Relative primary energy saving %	%	55	58	59	61	62	
23	Specific primary energy savings	kWh_{PE}/m^2	210	194	178	165	151	
24	Total Investment Cost	INR	2639600	2702100	2764600	2827100	2889600	350000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	269240	275615	281980	288365	294740	60900
27	Maintenance cost	INR	35406	36031	36656	37281	37906	5250
28	Annual electricity cost	INR	33266	31371	30149	29039	28174	74179
29	Total annual cost	INR	337912	343017	348795	354685	360820	140329
30	Annual operation and maintenance cost	INR	68673	67403	66806	66321	66081	79479
31	Annual extra cost of solar system	INR	197584	202689	208467	214357	220492	
32	Cost of saved primary energy	INR/kWh	13.12	12.86	12.86	12.90	13.02	
33	Payback time	Years	213	196	191	189	190	

A-5 Moderate climate (Bangalore) – ETC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	150742	169585	193139	211981	230824	
3	Solar heat production	kWh	38226	38499	38792	37876	37573	
4	Solar heat contribution -cooling	kWh	34969	35241	35536	34624	34319	
5	Total cooling energy demand	kWh	30098	30103	30111	30109	30105	
6	Solar cooling produced by absorption chiller	kWh	25755	26073	26611	26510	26341	
7	Auxiliary cooling-back up chiller	kWh	4343	4030	3500	3599	3764	
8	Net collector efficiency	%	0.25	0.23	0.20	0.18	0.16	
9	Solar fraction	Unit less	0.86	0.87	0.88	0.88	0.87	
10	Annual incident radiation per unit collector area	kWh/m^2	2094	2094	2146	2094	2094	
11	Specific useful net collector output	kWh/m2	531	475	431	374	341	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	1241	1151	1000	1028	1075	
13	Annual power consumption by pumps	kWh_{el}	1960	1977	2011	2003	1980	
14	Total annual tower consumption	kWh_{el}	3201	3128	3011	3031	3055	
15	Electrical COP absorption chiller	Unit less	10	10	10	10	10	
16	Cooling tower power consumption	kWh_{el}	607	613	621	611	607	
17	Electrical COP system	Unit less	7.90	8.05	8.29	8.27	8.22	
18	Electrical consumption -reference	kWh_{el}						9825
19	Annual primary energy consumption - Reference	kWh_{PE}						27292
20	Annual primary energy consumption -thermal	kWh_{PE}	8891	8690	8364	8420	8487	
21	Relative primary energy savings	kWh_{PE}	18400	18602	18928	18872	18804	
22	Relative primary energy saving %	%	67	68	69	69	69	
23	Specific primary energy savings	kWh_{PE}/m^2	256	230	210	186	171	
24	Total Investment Cost	INR	2853100	2946100	3039100	3132100	3225100	350000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	291016	300502	309988	39474	328960	60900
27	Maintenance cost	INR	37542	38472	39402	40332	41262	5250
28	Annual electricity cost	INR	24166	23620	22733	22886	23068	74179
29	Total annual cost	INR	352724	362593	372123	382692	393290	140329
30	Annual operation and maintenance cost	INR	61708	62091	62135	63218	64330	79479
31	Annual extra cost of solar system	INR	212395	222264	231794	242362	252691	
32	Cost of saved primary energy	INR/kWh	11.54	11.95	12.25	12.84	13.45	
33	Payback time	Years	141	150	155	172	190	

A-6 Moderate climate (Bangalore) – CPC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	146315	170701	190210	209718	234104	
3	Solar heat production	kWh	38398	38178	37486	37028	36493	
4	Solar heat contribution -cooling	kWh	35168	34952	34263	33806	33271	
5	Total cooling energy demand	kWh	30118	30119	30120	30120	30118	
6	Solar cooling produced by absorption chiller	kWh	28015	28210	28223	28263	28081	
7	Auxiliary cooling-back up chiller	kWh	2103	1909	1897	1857	2037	
8	Net collector efficiency	%	0.26	0.22	0.20	0.18	0.16	
9	Solar fraction	Unit less	0.93	0.94	0.94	0.94	0.93	
10	Annual incident radiation per unit collector area	kWh/m^2	2093	2093	2093	2093	2093	
11	Specific useful net collector output	kWh/m2	549	468	413	370	326	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	601	545	542	531	582	
13	Annual power consumption by pumps	kWh_{el}	2031	2046	2047	2049	2037	
14	Total annual tower consumption	kWh_{el}	2632	2591	2589	2580	2619	
15	Electrical COP absorption chiller	Unit less	11	11	11	11	11	
16	Cooling tower power consumption	kWh_{el}	632	632	625	621	614	
17	Electrical COP system	Unit less	9.23	9.34	9.37	9.41	9.32	
18	Electrical consumption -reference	kWh_{el}						9825
19	Annual primary energy consumption - Reference	kWh_{PE}						27292
20	Annual primary energy consumption -thermal	kWh_{PE}	7311	7198	7192	7165	7275	
21	Relative primary energy savings	kWh_{PE}	19981	20093	20100	20126	20017	
22	Relative primary energy saving %	%	73	74	74	74	73	
23	Specific primary energy savings	kWh_{PE}/m^2	285.8505	246.3918	221.195	200.88	178.9759	
24	Total Investment Cost	INR	3147100	3282100	3417100	3552100	3687100	350000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	321004	334774	348544	362314	376084	60900
27	Maintenance cost	INR	40481	41832	43182	44532	45882	5250
28	Annual electricity cost	INR	19871	19565	19547	19476	19773	74179
29	Total annual cost	INR	381356	396171	411273	426322	441739	140329
30	Annual operation and maintenance cost	INR	60352	61397	62728	64007	65655	79479
31	Annual extra cost of solar system	INR	241027	255842	270944	285993	301410	
32	Cost of saved primary energy	INR/kWh	12.06	12.73	13.48	14.20	15.05	
33	Payback time	Years	147	163	184	208	242	

A-7 Warm and humid climate (Chennai) – FPC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	146231	165729	185226	204724	229096	
3	Solar heat production	kWh	33319	37613	41266	44611	48573	
4	Solar heat contribution -cooling	kWh	30698	34991	38637	41972	45924	
5	Total cooling energy demand	kWh	51199	51220	51227	51249	51263	
6	Solar cooling produced by absorption chiller	kWh	26298	29490	31930	34024	36307	
7	Auxiliary cooling-back up chiller	kWh	24901	21730	19297	17225	14956	
8	Net collector efficiency	%	0.23	0.23	0.22	0.22	0.21	
9	Solar fraction	Unit less	0.51	0.58	0.62	0.66	0.71	
10	Annual incident radiation per unit collector area	kWh/m^2	2039	2039	2039	2039	2039	
11	Specific useful net collector output	kWh/m2	465	463	454	444	432	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	7115	6209	5513	4921	4273	
13	Annual power consumption by pumps	kWh_{el}	2824	3117	3301	3534	3739	
14	Total annual tower consumption	kWh_{el}	9939	9326	8814	8455	8012	
15	Electrical COP absorption chiller	Unit less	7.75	7.84	7.97	7.92	7.96	
16	Cooling tower power consumption	kWh_{el}	569.96	644.81	705.67	759.96	822.31	
17	Electrical COP system	Unit less	4.87	5.14	5.38	5.56	5.80	
18	Electrical consumption -reference	kWh_{el}						17912
19	Annual primary energy consumption - Reference	kWh_{PE}						49756
20	Annual primary energy consumption -thermal	kWh_{PE}	27607	25904	24485	23487	22256	
21	Relative primary energy savings	kWh_{PE}	22148	23851	25271	26268	27500	
22	Relative primary energy saving %	%	45	48	51	53	55	
23	Specific primary energy savings	kWh_{PE}/m^2	309	294	278	262	245	
24	Total Investment Cost	INR	3179600	3242100	3304600	3367100	3429600	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	324319	330694	337069	343444	349819	87000
27	Maintenance cost	INR	43507	44132	44757	45382	46007	7500
28	Annual electricity cost	INR	75036	70408	66549	63838	60492	135236
29	Total annual cost	INR	442862	445234	448375	452664	456317	229736
30	Annual operation and maintenance cost	INR	118543	114540	111305	109220	106498	142736
31	Annual extra cost of solar system	INR	213126	215498	218639	222928	226581	
32	Cost of saved primary energy	INR/kWh	9.62	9.04	8.65	8.49	8.24	
33	Payback time	Years	110.76	97.25	89.23	85.54	80.84	

A-8 Warm and humid climate (Chennai) – ETC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	146797	165146	188083	206433	224782	
3	Solar heat production	kWh	53894	58323	62377	64713	65632	
4	Solar heat contribution -cooling	kWh	51249	55661	59703	62033	62945	
5	Total cooling energy demand	kWh	51303	51312	51323	51329	51324	
6	Solar cooling produced by absorption chiller	kWh	40604	42232	43715	44594	44383	
7	Auxiliary cooling-back up chiller	kWh	10699	9080	7608	6735	6941	
8	Net collector efficiency	%	0.37	0.35	0.33	0.31	0.29	
9	Solar fraction	Unit less	0.79	0.82	0.85	0.87	0.86	
10	Annual incident radiation per unit collector area	kWh/m^2	2039	2039	2090	2039	2039	
11	Specific useful net collector output	kWh/m2	749	720	693	639	595	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	3057	2594	2174	1924	1983	
13	Annual power consumption by pumps	kWh_{el}	4183	4183	4183	4183	4183	
14	Total annual tower consumption	kWh_{el}	7240	6777	6356	6107	6166	
15	Electrical COP absorption chiller	Unit less	7.96	8.18	8.38	8.50	8.44	
16	Cooling tower power consumption	kWh_{el}	919	979	1034	1066	1073	
17	Electrical COP system	Unit less	6.29	6.62	6.94	7.16	7.09	
18	Electrical consumption -reference	kWh_{el}						17912
19	Annual primary energy consumption - Reference	kWh_{PE}						49756
20	Annual primary energy consumption -thermal	kWh_{PE}	20110	18825	17657	16964	17127	
21	Relative primary energy savings	kWh_{PE}	29646	30931	32099	32792	32628	
22	Relative primary energy saving %	%	60	62	65	66	66	
23	Specific primary energy savings	kWh_{PE}/m^2	412	382	357	324	296	
24	Total Investment Cost	INR	3393100	3486100	3579100	3672100	3765100	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	346096	355582	365068	374554	384040	87000
27	Maintenance cost	INR	45642	46572	47502	48432	49362	7500
28	Annual electricity cost	INR	54659	51166	47991	46108	46552	135236
29	Total annual cost	INR	446396	453320	460561	469093	479954	229736
30	Annual operation and maintenance cost	INR	100300	97738	95492	94539	95914	142736
31	Annual extra cost of solar system	INR	216660	223584	230825	239357	250218	
32	Cost of saved primary energy	INR/kWh	7.31	7.23	7.19	7.30	7.67	
33	Payback time	Years	68.18	66.36	65.17	65.82	69.73	

A-9 Warm and humid climate (Chennai) – CPC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	142481	166228	185225	204223	227970	
3	Solar heat production	kWh	54996	60253	61372	64856	63599	
4	Solar heat contribution -cooling	kWh	52357	57599	58725	62189	60929	
5	Total cooling energy demand	kWh	51311	51327	51324	51325	51311	
6	Solar cooling produced by absorption chiller	kWh	42576	44762	44811	45379	44006	
7	Auxiliary cooling-back up chiller	kWh	8735	6565	6513	5946	7305	
8	Net collector efficiency	%	0.39	0.36	0.33	0.32	0.28	
9	Solar fraction	Unit less	0.83	0.87	0.87	0.88	0.86	
10	Annual incident radiation per unit collector area	kWh/m^2	2038	2038	2038	2038	2038	
11	Specific useful net collector output	kWh/m2	787	739	675	647	569	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	2496	1876	1861	1699	2087	
13	Annual power consumption by pumps	kWh_{el}	4169	4414	4383	4417	4247	
14	Total annual tower consumption	kWh_{el}	6665	6290	6244	6116	6334	
15	Electrical COP absorption chiller	Unit less	8.32	8.23	8.27	8.26	8.31	
16	Cooling tower power consumption	kWh_{el}	949	1024	1035	1076	1049	
17	Electrical COP system	Unit less	6.74	7.02	7.05	7.14	6.95	
18	Electrical consumption -reference	kWh_{el}						17912
19	Annual primary energy consumption - Reference	kWh_{PE}						49756
20	Annual primary energy consumption -thermal	kWh_{PE}	18513	17471	17344	16988	17595	
21	Relative primary energy savings	kWh_{PE}	31242	32284	32412	32767	32161	
22	Relative primary energy saving %	%	63	65	65	66	65	
23	Specific primary energy savings	kWh_{PE}/m^2	447	396	357	327	288	
24	Total Investment Cost	INR	3687100	3822100	3957100	4092100	4227100	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	376084	389854	403624	417394	431164	87000
27	Maintenance cost	INR	48582	49932	51282	52632	53982	7500
28	Annual electricity cost	INR	50319	47487	47141	46175	47823	135236
29	Total annual cost	INR	474984	487273	502047	516200	532968	229736
30	Annual operation and maintenance cost	INR	98900	97419	98423	98806	101804	142736
31	Annual extra cost of solar system	INR	245248	257537	272311	286464	303232	
32	Cost of saved primary energy	INR/kWh	7.85	7.98	8.40	8.74	9.43	
33	Payback time	Years	72.71	73.31	78.02	81.77	91.06	

A-10 Composite Climate (Delhi) – FPC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	155338	176049	196760	216877	242694	
3	Solar heat production	kWh	32061	35155	37888	39999	42598	
4	Solar heat contribution -cooling	kWh	28890	31974	34696	36799	39390	
5	Total cooling energy demand	kWh	36200	36215	36224	36230	36236	
6	Solar cooling produced by absorption chiller	kWh	22670	24372	26001	26915	28125	
7	Auxiliary cooling-back up chiller	kWh	13530	11843	10223	9315	8111	
8	Net collector efficiency	%	0.21	0.20	0.19	0.18	0.18	
9	Solar fraction	Unit less	0.63	0.67	0.72	0.74	0.78	
10	Annual incident radiation per unit collector area	kWh/m^2	2166	2166	2166	2161	2161	
11	Specific useful net collector output	kWh/m2	447	433	417	398	379	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	3866	3384	2921	2661	2317	
13	Annual power consumption by pumps	kWh_{el}	2121	2230	2334	2413	2500	
14	Total annual tower consumption	kWh_{el}	5987	5614	5255	5074	4817	
15	Electrical COP absorption chiller	Unit less	8.60	8.72	8.84	8.82	8.86	
16	Cooling tower power consumption	kWh_{el}	516	563	607	637	675	
17	Electrical COP system	Unit less	5.57	5.86	6.18	6.34	6.60	
18	Electrical consumption -reference	kWh_{el}						12331
19	Annual primary energy consumption - Reference	kWh_{PE}						34253
20	Annual primary energy consumption -thermal	kWh_{PE}	16630	15594	14598	14095	13381	
21	Relative primary energy savings	kWh_{PE}	17623	18659	19655	20157	20872	
22	Relative primary energy saving %	%	51	54	57	59	61	
23	Specific primary energy savings	kWh_{PE}/m^2	246	230	216	201	186	
24	Total Investment Cost	INR	3179600	3242100	3304600	3367100	3429600	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	324319	330694	337069	343444	349819	87000
27	Maintenance cost	INR	43507	44132	44757	45382	46007	7500
28	Annual electricity cost	INR	45200	42385	39676	38311	36369	93099
29	Total annual cost	INR	413025	417211	421502	427137	432195	187599
30	Annual operation and maintenance cost	INR	88706	86517	84433	83693	82376	100599
31	Annual extra cost of solar system	INR	225425	229611	233902	239537	244595	
32	Cost of saved primary energy	INR/kWh	12.79	12.31	11.90	11.88	11.72	
33	Payback time	Years	225.30	194.70	173.48	169.58	160.75	

A-11Composite Climate (Delhi) – ETC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	155756	175224	198918	218323	237727	
3	Solar heat production	kWh	44529	46297	48702	50022	50985	
4	Solar heat contribution -cooling	kWh	41336	43101	45500	46818	46206	
5	Total cooling energy demand	kWh	36250	36258	36267	36265	36265	
6	Solar cooling produced by absorption chiller	kWh	30202	31403	32377	32822	33044	
7	Auxiliary cooling-back up chiller	kWh	6048	4855	3890	3443	3221	
8	Net collector efficiency	%	0.29	0.26	0.24	0.23	0.21	
9	Solar fraction	Unit less	0.83	0.87	0.89	0.91	0.91	
10	Annual incident radiation per unit collector area	kWh/m^2	2163	2163	2210	2156	2156	
11	Specific useful net collector output	kWh/m2	618	572	541	494	462	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	1728	1387	1111	984	920	
13	Annual power consumption by pumps	kWh_{el}	2646	2759	2895	2901	2906	
14	Total annual tower consumption	kWh_{el}	4374	4147	4006	3885	3827	
15	Electrical COP absorption chiller	Unit less	8.98	8.96	8.81	8.88	8.93	
16	Cooling tower power consumption	kWh_{el}	715	745	779	796	793	
17	Electrical COP system	Unit less	7.12	7.41	7.58	7.75	7.85	
18	Electrical consumption -reference	kWh_{el}						12331
19	Annual primary energy consumption - Reference	kWh_{PE}						34253
20	Annual primary energy consumption -thermal	kWh_{PE}	12151	11518	11128	10792	10630	
21	Relative primary energy savings	kWh_{PE}	22102	22735	23125	23461	23623	
22	Relative primary energy saving %	%	65	66	68	68	69	
23	Specific primary energy savings	kWh_{PE}/m^2	307	281	257	232	214	
24	Total Investment Cost	INR	3393100	3486100	3579100	3672100	3765100	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	346096	355582	365068	374554	384040	87000
27	Maintenance cost	INR	45642	46572	47502	48432	49362	7500
28	Annual electricity cost	INR	33027	31306	30246	29333	28891	93099
29	Total annual cost	INR	424765	433460	442816	452318	462293	187599
30	Annual operation and maintenance cost	INR	78668	77878	77748	77764	78253	100599
31	Annual extra cost of solar system	INR	237165	245860	255216	264718	274693	
32	Cost of saved primary energy	INR/kWh	10.73	10.81	11.04	11.28	11.63	
33	Payback time	Years	131.91	131.42	134.74	138.91	146.11	

A-12 Composite Climate (Delhi) – CPC

S.No	Parameter	Unit	Value					Reference
1	Collector area	m^2	70	80	90	100	110	
2	Annual solar radiation on collector	kWh	151048	176220	196358	215721	240801	
3	Solar heat production	kWh	44435	46351	48184	49955	50042	
4	Solar heat contribution -cooling	kWh	41287	43184	45011	46776	46889	
5	Total cooling energy demand	kWh	36264	36264	36262	36263	36263	
6	Solar cooling produced by absorption chiller	kWh	32123	32821	33335	33682	33718	
7	Auxiliary cooling-back up chiller	kWh	4141	3443	2927	2581	2545	
8	Net collector efficiency	%	0.29	0.26	0.25	0.23	0.21	
9	Solar fraction	Unit less	0.89	0.91	0.92	0.93	0.93	
10	Annual incident radiation per unit collector area	kWh/m^2	2161	2161	2161	2153	2153	
11	Specific useful net collector output	kWh/m2	636	568	530	499	447	
12	Electrical auxiliary consumption -backup chiller	kWh_{el}	1183	984	836	737	727	
13	Annual power consumption by pumps	kWh_{el}	2495	2780	2809	2810	2762	
14	Total annual tower consumption	kWh_{el}	3678	3764	3645	3547	3489	
15	Electrical COP absorption chiller	Unit less	9.95	9.27	9.28	9.32	9.45	
16	Cooling tower power consumption	kWh_{el}	734	760	783	805	806	
17	Electrical COP system	Unit less	8.22	8.02	8.19	8.33	8.44	
18	Electrical consumption -reference	kWh_{el}						12331
19	Annual primary energy consumption - Reference	kWh_{PE}						34253
20	Annual primary energy consumption -thermal	kWh_{PE}	10217	10455	10126	9854	9692	
21	Relative primary energy savings	kWh_{PE}	24036	23798	24127	24399	24561	
22	Relative primary energy saving %	%	70	69	70	71	72	
23	Specific primary energy savings	kWh_{PE}/m^2	344	292	266	244	220	
24	Total Investment Cost	INR	3687100	3822100	3957100	4092100	4227100	500000
25	Annuity factor	%	10.2	10.2	10.2	10.2	10.2	17.4
26	Annual capital cost	INR	376084	389854	403624	417394	431164	87000
27	Maintenance cost	INR	48582	49932	51282	52632	53982	7500
28	Annual electricity cost	INR	27770	28416	27522	26783	26343	93099
29	Total annual cost	INR	452436	468202	482428	496809	511489	187599
30	Annual operation and maintenance cost	INR	76351	78348	78803	79415	80325	100599
31	Annual extra cost of solar system	INR	264836	280602	294828	309209	323889	
32	Cost of saved primary energy	INR/kWh	11.02	11.79	12.22	12.67	13.19	
33	Payback time	Years	131.43	149.29	158.61	169.56	183.82	

Appendix: B1-12 Solar Photovoltaic Cooling System - Energy and cost performance sheet

B-1 Hot and dry climate (Ahmedabad) – Monocrystalline PV cells

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	20468	23324	26180	29035	31891	
4	Annual power to load	kWh_{el}	5712	6509	7306	8103	8891	
5	Annual power consumption by air conditioner	kWh_{el}	15619	15619	15619	15619	15619	
6	Annual power consumption from grid	kWh_{el}	9907	9110	8313	7516	6728	
7	Annual useful power output	kWh_{el}	19854	22624	25394	28164	30935	
8	Annual excess power	kWh_{el}	14142	16115	18088	20061	22044	
9	Annual cooling energy demand	kWh_{th}	44650	44650	44650	44650	44650	
10	Solar fraction-Grid supported	Unit less	0.37	0.42	0.47	0.52	0.57	
11	Solar Fraction- net metering	Unit less	1.27	1.45	1.63	1.80	1.98	
12	Electrical (grid)COP	Unit less	4.51	4.90	5.37	5.94	6.64	
13	Energy savings (Grid supported)	kWh_{el}	5712	6509	7306	8103	8891	
14	Primary energy consumption (Reference)	kWh_{PE}	43385	43385	43385	43385	43385	
15	Primary energy consumption(Grid power)	kWh_{PE}	27519	25305	23091	20877	18688	
16	Primary energy saving (Grid supported)	kWh_{PE}	15867	18081	20295	22508	24697	
17	Primary energy saving % (Grid supported)	Unit less	37	42	47	52	57	
18	Specific primary energy savings (Grid supported)	kWh_{PE}/m^2	227	226	225	225	225	
19	Total investment cost	INR	1140309	1229655	1319000	1408345	1497691	500000
20	Annual capital cost	INR	146991	155361	163730	172100	180470	87000
21	Maintenance cost	INR	14847	15872	16898	17923	18948	7500
22	Annual electricity cost (Grid supported)	INR	74795	68778	62760	56743	50794	117921
23	Total Annual cost	INR	236633	240011	243388	246766	250212	212421
24	Annual operation and maintenance cost	INR	89643	84650	79658	74666	69742	125421
25	Annual extra cost of solar system	INR	24212	27590	30967	34345	37791	
26	Cost per unit of primary energy saved	INR	1.53	1.53	1.53	1.53	1.53	
27	Payback time (Grid supported)	Years	17.90	17.90	17.90	17.90	17.92	
28	Cost of electricity generated by PV -net metering	INR	149895	170810	191726	212641	233557	
29	Cost of maintenance-net metering	INR	6403	7297	8190	9083	9977	
30	Payback-net metering	Years	4.49	4.49	4.49	4.49	4.49	

B-2 Hot and dry climate (Ahmedabad) – Polycrystalline PV cells

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10	11.25	12.75	14.25	15.5	
3	Annual power generation	kWh_{el}	18853	20960	23755	26550	28879	
4	Annual power to load	kWh_{el}	5294	5878	6661	7445	8094	
5	Annual power consumption by air conditioner	kWh_{el}	15619	15619	15619	15619	15619	
6	Annual power consumption from grid	kWh_{el}	10325	9741	8957	8174	7525	
7	Annual useful power output	kWh_{el}	18287	20332	23042	25753	28012	
8	Annual excess power	kWh_{el}	12994	14454	16381	18308	19919	
9	Annual cooling energy demand	kWh_{th}	44650	44650	44650	44650	44650	
10	Solar fraction-Grid supported	Unit less	0.34	0.38	0.43	0.48	0.52	
11	Solar Fraction- net metering	Unit less	1.17	1.30	1.48	1.65	1.79	
12	Electrical (grid)COP	Unit less	4.32	4.58	4.98	5.46	5.93	
13	Energy savings (Grid supported)	kWh_{el}	5294	5878	6661	7445	8094	
14	Primary energy consumption (Reference)	kWh_{PE}	43385	43385	43385	43385	43385	
15	Primary energy consumption(Grid power)	kWh_{PE}	28680	27059	24882	22705	20903	
16	Primary energy saving(Grid supported)	kWh_{PE}	14705	16326	18503	20680	22482	
17	Primary energy saving %(grid supported)	Unit less	34	38	43	48	52	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	210	204	206	207	204	
19	Total investment cost	INR	1067273	1138182	1223273	1308364	1379273	500000
20	Annual capital cost	INR	140149	146791	154763	162734	169377	87000
21	Maintenance cost	INR	14009	14823	15799	16775	17589	7500
22	Annual electricity cost (Grid supported)	INR	77953	73546	67629	61712	56815	117921
23	Total Annual cost	INR	232111	235160	238191	241221	243781	212421
24	Annual operation and maintenance cost	INR	91963	88368	83428	78488	74404	125421
25	Annual extra cost of solar system	INR	19690	22739	25770	28800	31360	
26	Cost per unit of primary energy saved	INR	1.34	1.39	1.39	1.39	1.39	
27	Payback time (Grid supported)	Years	16.95	17.22	17.22	17.22	17.23	
28	Cost of electricity generated by PV -net metering	INR	138070	153503	173970	194437	211493	
29	Cost of maintenance-net metering	INR	5673	6382	7233	8084	8793	
30	Payback-net metering	Years	4.37	4.37	4.37	4.37	4.37	

B-3 Hot and dry climate (Ahmedabad) – Thinfilm cell

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	8	9.125	10.25	11.5	12.635	
3	Annual power generation	kWh_{el}	15557	17745	19932	22363	24551	
4	Annual power to load	kWh_{el}	4423	5045	5667	6358	6980	
5	Annual power consumption by air conditioner	kWh_{el}	15619	15619	15619	15619	15619	
6	Annual power consumption from grid	kWh_{el}	11196	10574	9952	9261	8639	
7	Annual useful power output	kWh_{el}	15090	17212	19334	21692	23814	
8	Annual excess power	kWh_{el}	10667	12168	13668	15335	16835	
9	Annual cooling energy demand	kWh_{th}	44650	44650	44650	44650	44650	
10	Solar fraction-Grid supported	Unit less	0.28	0.32	0.36	0.41	0.45	
11	Solar Fraction- net metering	Unit less	0.97	1.10	1.24	1.39	1.52	
12	Electrical (grid)COP	Unit less	3.99	4.22	4.49	4.82	5.17	
13	Energy savings (Grid supported)	kWh_{el}	4423	5045	5667	6358	6980	
14	Primary energy consumption (Reference)	kWh_{PE}	43385	43385	43385	43385	43385	
15	Primary energy consumption(Grid power)	kWh_{PE}	31100	29372	27645	25725	23998	
16	Primary energy saving(Grid supported)	kWh_{PE}	12285	14013	15740	17660	19388	
17	Primary energy saving %(grid supported)	Unit less	28	32	36	41	45	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	176	175	175	177	176	
19	Total investment cost	INR	908436	965873	1023309	1087127	1144564	500000
20	Annual capital cost	INR	125269	130650	136030	142009	147389	87000
21	Maintenance cost	INR	12187	12846	13505	14237	14896	7500
22	Annual electricity cost (Grid supported)	INR	84530	79834	75139	69921	65226	117921
23	Total Annual cost	INR	221986	223330	224674	226167	227511	212421
24	Annual operation and maintenance cost	INR	96716	92680	88643	84158	80122	125421
25	Annual extra cost of solar system	INR	9565	10909	12253	13746	15090	
26	Cost per unit of primary energy saved	INR	0.78	0.78	0.78	0.78	0.78	
27	Payback time (Grid supported)	Years	14.23	14.23	14.23	14.23	14.23	
28	Cost of electricity generated by PV -net metering	INR	113931	129952	145974	163775	179797	
29	Cost of maintenance-net metering	INR	4084	4659	5233	5871	6446	
30	Payback-net metering	Years	3.74	3.74	3.74	3.74	3.74	

B-4 Moderate climate (Bangalore) – Monocrystalline PV cells

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	19772	22531	25204	28048	30807	
4	Annual power to load	kWh_{el}	4601	5130	5443	5746	5923	
5	Annual power consumption by air conditioner	kWh_{el}	9825	9825	9825	9825	9825	
6	Annual power consumption from grid	kWh_{el}	5286	4756	4443	4140	3964	
7	Annual useful power output	kWh_{el}	19179	21404	23944	26646	29267	
8	Annual excess power	kWh_{el}	14578	16724	19004	21460	23960	
9	Annual cooling energy demand	kWh_{th}	30060	30060	30060	30060	30060	
10	Solar fraction-Grid supported	Unit less	0.47	0.52	0.55	0.58	0.60	
11	Solar Fraction- net metering	Unit less	1.95	2.18	2.44	2.71	2.98	
12	Electrical (grid)COP	Unit less	5.69	6.32	6.76	7.26	7.58	
13	Energy savings (Grid supported)	kWh_{el}	4601	5130	5443	5746	5923	
14	Primary energy consumption (Reference)	kWh_{PE}	27293	27293	27293	27293	27293	
15	Primary energy consumption(Grid power)	kWh_{PE}	14685	13214	12344	11503	11012	
16	Primary energy saving(Grid supported)	kWh_{PE}	12779.9	14251.1	15120.3	15962.1	16452.7	
17	Primary energy saving %(grid supported)	Unit less	46.53	51.89	55.05	58.12	59.90	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	183	178	168	168	170	
19	Total investment cost	INR	990309	1079655	1169100	1258345	1347691	350000
20	Annual capital cost	INR	120889	129258	137628	145998	154368	60900
21	Maintenance cost	INR	12597	13622	14648	15673	16698	5250
22	Annual electricity cost (Grid supported)	INR	39913	35915	33552	31264	29931	74182
23	Total Annual cost	INR	173399	178795	185828	192934	200996	140332
24	Annual operation and maintenance cost	INR	52510	49537	48200	46937	46628	79432
25	Annual extra cost of solar system	INR	33066.94	38463.22	45495.64	52602.46	60664.00	
26	Cost per unit of primary energy saved	INR	2.59	2.70	3.01	3.30	3.69	
27	Payback time (Grid supported)	Years	26	26.43	26.22	26.95	26.12	
28	Cost of electricity generated by PV -net metering	INR	144798	161600	180774	201176	220964	
29	Cost of maintenance-net metering	INR	6403	7297	8190	9083	9977	
30	Payback-net metering	Years	4.76	4.76	4.78	4.76	4.76	

B-5 Moderate climate (Bangalore) – Polycrystalline PV cells

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10	11.25	12.75	14.25	15.5	
3	Annual power generation	kWh_{el}	18094	20356	23070	25784	28046	
4	Annual power to load	kWh_{el}	4239	4712	5144	5451	5639	
5	Annual power consumption by air conditioner	kWh_{el}	9825	9825	9825	9825	9825	
6	Annual power consumption from grid	kWh_{el}	5648	5175	4744	4436	4249	
7	Annual useful power output	kWh_{el}	17551	19745	22378	25011	27204	
8	Annual excess power	kWh_{el}	13312	15033	17234	19560	21566	
9	Annual cooling energy demand	kWh_{th}	30060	30060	30060	30060	30060	
10	Solar fraction-Grid supported	Unit less	0.43	0.48	0.52	0.55	0.57	
11	Solar Fraction- net metering	Unit less	1.79	2.01	2.28	2.55	2.77	
12	Electrical (grid)COP	Unit less	5.32	5.81	6.34	6.78	7.08	
13	Energy savings (Grid supported)	kWh_{el}	4239	4712	5144	5451	5639	
14	Primary energy consumption (Reference)	kWh_{PE}	27293	27293	27293	27293	27293	
15	Primary energy consumption(Grid power)	kWh_{PE}	15689	14375	13177	12323	11802	
16	Primary energy saving(Grid supported)	kWh_{PE}	11776	13089	14288	15141	15663	
17	Primary energy saving %(grid supported)	Unit less	43	48	52	55	57	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	161	164	159	151	155	
19	Total investment cost	INR	917273	988182	1073273	1158364	1229273	350000
20	Annual capital cost	INR	114047	120689	128660	136632	143274	60900
21	Maintenance cost	INR	11759	12573	13549	14525	15339	5250
22	Annual electricity cost (Grid supported)	INR	42642	39072	35814	33495	32077	74182
23	Total Annual cost	INR	168447	172334	178024	184652	190691	140332
24	Annual operation and maintenance cost	INR	54401	51645	49363	48020	47416	79432
25	Annual extra cost of solar system	INR	28115	32002	37692	44320	50359	
26	Cost per unit of primary energy saved	INR	2.39	2.44	2.64	2.93	3.22	
27	Payback time (Grid supported)	Years	23.66	23.97	24.05	25.73	27.46	
28	Cost of electricity generated by PV -net metering	INR	132512	149076	168953	188830	205393	
29	Cost of maintenance-net metering	INR	5673	6382	7233	8084	8793	
30	Payback-net metering	Years	4.50	4.50	4.50	4.50	4.50	

B-6 Moderate climate (Bangalore) – Thinfilm cell

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m2	70	80	90	100	110	
2	PV capacity	kW	8	9.125	10.25	11.5	12.635	
3	Annual power generation	kWhel	14430	16459	18488	20743	22772	
4	Annual power to load	kWhel	3407	3885	4348	4801	5123	
5	Annual power consumption by air conditioner	kWhel	9825	9825	9825	9825	9825	
6	Annual power consumption from grid	kWhel	6481	6003	5539	5086	4764	
7	Annual useful power output	kWhel	13997	15965	17934	20121	22089	
8	Annual excess power	kWhel	10591	12081	13585	15320	16966	
9	Annual cooling energy demand	kWhth	30060	30060	30060	30060	30060	
10	Solar fraction-Grid supported	Unit less	0.34	0.39	0.44	0.49	0.52	
11	Solar Fraction- net metering	Unit less	1.42	1.62	1.83	2.05	2.25	
12	Electrical (grid)COP	Unit less	4.14	4.36	4.60	4.91	5.21	
13	Energy savings (Grid supported)	kWhel	3407	3885	4348	4801	5123	
14	Primary energy consumption (Reference)	kWhPE	27293	27293	27293	27293	27293	
15	Primary energy consumption(Grid power)	kWhPE	18002	16674	15386	14128	13233	
16	Primary energy saving(Grid supported)	kWhPE	9463	10791	12079	13336	14232	
17	Primary energy saving %(grid supported)	Unit less	34	39	44	49	52	
18	Specific primary energy savings(Grid supported)	kWhPE/m2	135	135	134	133	129	
19	Total investment cost	INR	758436	815873	873309	937127	994564	350000
20	Annual capital cost	INR	99167	104548	109928	115907	121287	60900
21	Maintenance cost	INR	9937	10596	11255	11987	12646	5250
22	Annual electricity cost (Grid supported)	INR	48930	45320	41819	38401	35967	74182
23	Total Annual cost	INR	158033	160463	163002	166294	169900	140332
24	Annual operation and maintenance cost	INR	58866	55915	53074	50388	48613	79432
25	Annual extra cost of solar system	INR	17701	20131	22670	25962	29568	
26	Cost per unit of primary energy saved	INR	1.87	1.87	1.88	1.95	2.08	
27	Payback time (Grid supported)	Years	19.86	19.81	19.85	20.22	20.92	
28	Cost of electricity generated by PV -net metering	INR	105678	120539	135400	151912	166773	
29	Cost of maintenance-net metering	INR	4084	4659	5233	5871	6446	
30	Payback-net metering	Years	4.04	4.04	4.04	4.04	4.04	

B-7 Warm and humid climate (Chennai) – Monocrystalline PV cells

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	17639	20100	22561	25023	27484	
4	Annual power to load	kWh_{el}	5669	6460	7251	8043	8834	
5	Annual power consumption by air conditioner	kWh_{el}	17913	17913	17913	17913	17913	
6	Annual power consumption from grid	kWh_{el}	12244	11452	10661	9870	9079	
7	Annual useful power output	kWh_{el}	17110	19497	21885	24272	26659	
8	Annual excess power	kWh_{el}	11440	13037	14633	16229	17826	
9	Annual cooling energy demand	kWh_{th}	51220	51220	51220	51220	51220	
10	Solar fraction-Grid supported	Unit less	0.32	0.36	0.40	0.45	0.49	
11	Solar Fraction- net metering	Unit less	0.96	1.09	1.22	1.36	1.49	
12	Electrical (grid)COP	Unit less	4.18	4.47	4.80	5.19	5.64	
13	Energy savings (Grid supported)	kWh_{el}	5669	6460	7251	8043	8834	
14	Primary energy consumption (Reference)	kWh_{PE}	49758	49758	49758	49758	49758	
15	Primary energy consumption(Grid power)	kWh_{PE}	34010	31812	29615	27418	25220	
16	Primary energy saving(Grid supported)	kWh_{PE}	15748	17946	20143	22340	24538	
17	Primary energy saving %(grid supported)	Unit less	32	36	40	45	49	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	225	224	224	223	223	
19	Total investment cost	INR	1140309	######	1319000	1408345	1497691	500000
20	Annual capital cost	INR	146991	155361	163730	172100	180470	87000
21	Maintenance cost	INR	14847	15872	16898	17923	18948	7500
22	Annual electricity cost (Grid supported)	INR	92439	86466	80493	74521	68549	135242
23	Total Annual cost	INR	254276	257699	261121	264544	267966	229742
24	Annual operation and maintenance cost	INR	107286	102338	97391	92444	87497	142742
25	Annual extra cost of solar system	INR	24534	27957	31379	34802	38224	
26	Cost per unit of primary energy saved	INR	1.56	1.56	1.56	1.56	1.56	
27	Payback time (Grid supported)	Years	18.06	18.06	18.06	18.06	18.06	
28	Cost of electricity generated by PV -net metering	INR	129179	147204	165229	183253	201278	
29	Cost of maintenance-net metering	INR	6403	7297	8190	9083	9977	
30	Payback-net metering	Years	5.26	5.26	5.26	5.26	5.26	

B-8 Warm and humid climate (Chennai) – Polycrystalline PV cells

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10	11.25	12.75	14.25	15.5	
3	Annual power generation	kWh_{el}	15755	17725	20088	22452	24421	
4	Annual power to load	kWh_{el}	5119	5759	6527	7295	7935	
5	Annual power consumption by air conditioner	kWh_{el}	17913	17913	17913	17913	17913	
6	Annual power consumption from grid	kWh_{el}	12794	12154	11386	10618	9978	
7	Annual useful power output	kWh_{el}	15283	17193	19486	21778	23688	
8	Annual excess power	kWh_{el}	10164	11434	12959	14483	15754	
9	Annual cooling energy demand	kWh_{th}	51220	51220	51220	51220	51220	
10	Solar fraction-Grid supported	Unit less	0.29	0.32	0.36	0.41	0.44	
11	Solar Fraction- net metering	Unit less	0.85	0.96	1.09	1.22	1.32	
12	Electrical (grid)COP	Unit less	4.00	4.21	4.50	4.82	5.13	
13	Energy savings (Grid supported)	kWh_{el}	5119	5759	6527	7295	7935	
14	Primary energy consumption (Reference)	kWh_{PE}	49758	49758	49758	49758	49758	
15	Primary energy consumption(Grid power)	kWh_{PE}	35538	33760	31627	29494	27717	
16	Primary energy saving(Grid supported)	kWh_{PE}	14220	15998	18131	20264	22041	
17	Primary energy saving %(grid supported)	Unit less	29	32	36	41	44	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	203	200	201	203	200	
19	Total investment cost	INR	1067273	######	1223273	1308364	1379273	500000
20	Annual capital cost	INR	140149	146791	154763	162734	169377	87000
21	Maintenance cost	INR	14009	14823	15799	16775	17589	7500
22	Annual electricity cost (Grid supported)	INR	96592	91761	85963	80166	75335	135242
23	Total Annual cost	INR	250750	253375	256525	259675	262300	229742
24	Annual operation and maintenance cost	INR	110601	106583	101762	96941	92924	142742
25	Annual extra cost of solar system	INR	21008	23633	26783	29933	32558	
26	Cost per unit of primary energy saved	INR	1.48	1.48	1.48	1.48	1.48	
27	Payback time (Grid supported)	Years	17.65	17.65	17.65	17.65	17.65	
28	Cost of electricity generated by PV -net metering	INR	115385	129808	147116	164424	178847	
29	Cost of maintenance-net metering	INR	5673	6382	7233	8084	8793	
30	Payback-net metering	Years	5.21	5.21	5.21	5.21	5.21	

B-9 Warm and humid climate (Chennai) – Thin film cell

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	8	9.125	10.25	11.5	12.635	
3	Annual power generation	kWh_{el}	13039	14873	16706	18743	20341	
4	Annual power to load	kWh_{el}	4249	4847	5444	6108	6565	
5	Annual power consumption by air conditioner	kWh_{el}	17913	17913	17913	17913	17913	
6	Annual power consumption from grid	kWh_{el}	13664	13066	12469	11805	11347	
7	Annual useful power output	kWh_{el}	12648	14426	16205	18181	19730	
8	Annual excess power	kWh_{el}	8399	9580	10761	12073	13165	
9	Annual cooling energy demand	kWh_{th}	51220	51220	51220	51220	51220	
10	Solar fraction-Grid supported	Unit less	0.24	0.27	0.30	0.34	0.37	
11	Solar Fraction- net metering	Unit less	0.71	0.81	0.90	1.01	1.10	
12	Electrical (grid)COP	Unit less	3.75	3.92	4.11	4.34	4.51	
13	Energy savings (Grid supported)	kWh_{el}	4249	4847	5444	6108	6565	
14	Primary energy consumption (Reference)	kWh_{PE}	49758	49758	49758	49758	49758	
15	Primary energy consumption(Grid power)	kWh_{PE}	37955	36295	34636	32791	31521	
16	Primary energy saving(Grid supported)	kWh_{PE}	11803	13463	15122	16967	18237	
17	Primary energy saving %(grid supported)	Unit less	24	27	30	34	37	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	169	168	168	170	166	
19	Total investment cost	INR	908436	965873	1023309	1087127	1144564	500000
20	Annual capital cost	INR	125269	130650	136030	142009	147389	87000
21	Maintenance cost	INR	12187	12846	13505	14237	14896	7500
22	Annual electricity cost (Grid supported)	INR	103162	98651	94139	89127	85673	135242
23	Total Annual cost	INR	240618	242146	243674	245372	247958	229742
24	Annual operation and maintenance cost	INR	115348	111496	107644	103364	100569	142742
25	Annual extra cost of solar system	INR	10876	12404	13932	15630	18216	
26	Cost per unit of primary energy saved	INR	0.92	0.92	0.92	0.92	1.00	
27	Payback time (Grid supported)	Years	14.91	14.91	14.91	14.91	15.28	
28	Cost of electricity generated by PV -net metering	INR	95491	108919	122347	137268	148964	
29	Cost of maintenance-net metering	INR	4084	4659	5233	5871	6446	
30	Payback-net metering	Years	4.50	4.50	4.50	4.50	4.55	

B-10 Composite Climate (Delhi) –Monocrystalline PV cells

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	19517	22240	24963	27687	30410	
4	Annual power to load	kWh_{el}	4270	4866	5462	6057	6647	
5	Annual power consumption by air conditioner	kWh_{el}	12331	12331	12331	12331	12331	
6	Annual power consumption from grid	kWh_{el}	8061	7465	6870	6274	5685	
7	Annual useful power output	kWh_{el}	18931	21573	24214	26856	29497	
8	Annual excess power	kWh_{el}	14661	16707	18753	20799	22851	
9	Annual cooling energy demand	kWh_{th}	36200	36200	36200	36200	36200	
10	Solar fraction-Grid supported	Unit less	0.35	0.39	0.44	0.49	0.54	
11	Solar Fraction- net metering	Unit less	1.19	1.35	1.52	1.69	1.85	
12	Electrical (grid)COP	Unit less	4.49	4.85	5.27	5.77	6.37	
13	Energy savings (Grid supported)	kWh_{el}	4270	4866	5462	6057	6647	
14	Primary energy consumption (Reference)	kWh_{PE}	34254	34254	34254	34254	34254	
15	Primary energy consumption(Grid power)	kWh_{PE}	22392	20737	19082	17428	15790	
16	Primary energy saving(Grid supported)	kWh_{PE}	11861	13517	15172	16826	18464	
17	Primary energy saving %(grid supported)	Unit less	35	39	44	49	54	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	169	169	169	168	168	
19	Total investment cost	INR	1140309	1229655	1319000	1408345	1497691	500000
20	Annual capital cost	INR	146991	155361	163730	172100	180470	87000
21	Maintenance cost	INR	14847	15872	16898	17923	18948	7500
22	Annual electricity cost (Grid supported)	INR	60863	56364	51866	47370	42918	93102
23	Total Annual cost	INR	222701	227597	232493	237393	242336	187602
24	Annual operation and maintenance cost	INR	75710	72236	68763	65293	61866	100602
25	Annual extra cost of solar system	INR	35099	39995	44891	49791	54734	
26	Cost per unit of primary energy saved	INR	2.96	2.96	2.96	2.96	2.96	
27	Payback time (Grid supported)	Years	25.72	25.72	25.72	25.73	25.76	
28	Cost of electricity generated by PV -net metering	INR	142931	162875	182818	202762	222706	
29	Cost of maintenance-net metering	INR	6403	7297	8190	9083	9977	
30	Payback-net metering	Years	4.72	4.72	4.72	4.72	4.72	

B-11Composite Climate (Delhi) – Polycrystalline PV cells

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10	11.25	12.75	14.25	15.5	
3	Annual power generation	kWh_{el}	17717	19932	22589	25247	27462	
4	Annual power to load	kWh_{el}	3874	4358	4939	5520	6000	
5	Annual power consumption by air conditioner	kWh_{el}	12331	12331	12331	12331	12331	
6	Annual power consumption from grid	kWh_{el}	8458	7973	7392	6812	6332	
7	Annual useful power output	kWh_{el}	16831	18935	21460	23985	26089	
8	Annual excess power	kWh_{el}	12958	14577	16521	18465	20089	
9	Annual cooling energy demand	kWh_{th}	36200	36200	36200	36200	36200	
10	Solar fraction-Grid supported	Unit less	0.31	0.35	0.40	0.45	0.49	
11	Solar Fraction- net metering	Unit less	1.05	1.18	1.34	1.50	1.63	
12	Electrical (grid)COP	Unit less	4.28	4.54	4.90	5.31	5.72	
13	Energy savings (Grid supported)	kWh_{el}	3874	4358	4939	5520	6000	
14	Primary energy consumption (Reference)	kWh_{PE}	34254	34254	34254	34254	34254	
15	Primary energy consumption(Grid power)	kWh_{PE}	23494	22149	20535	18921	17588	
16	Primary energy saving(Grid supported)	kWh_{PE}	10760	12105	13719	15333	16666	
17	Primary energy saving %(grid supported)	Unit less	31	35	40	45	49	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	154	151	152	153	152	
19	Total investment cost	INR	1067273	1138182	1223273	1308364	1379273	500000
20	Annual capital cost	INR	140149	146791	154763	162734	169377	87000
21	Maintenance cost	INR	14009	14823	15799	16775	17589	7500
22	Annual electricity cost (Grid supported)	INR	63856	60200	55813	51428	47803	93102
23	Total Annual cost	INR	218014	221814	226375	230937	234769	187602
24	Annual operation and maintainance cost	INR	77865	75023	71612	68203	65392	100602
25	Annual extra cost of solar system	INR	30412	34212	38773	43335	47167	
26	Cost per unit of primary energy saved	INR	2.83	2.83	2.83	2.83	2.83	
27	Payback time (Grid supported)	Years	24.95	24.95	24.95	24.95	24.97	
28	Cost of electricity generated by PV -net metering	INR	127077	142961	162023	181084	196969	0
29	Cost of maintenance-net metering	INR	5673	6382	7233	8084	8793	0
30	Payback-net metering	Years	4.71	4.71	4.71	4.71	4.71	

B-12 Composite Climate (Delhi) – Thinfilm cell

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	8	9.125	10.25	11.5	12.635	
3	Annual power generation	kWh_{el}	14533	16576	18620	20891	22934	
4	Annual power to load	kWh_{el}	3288	3750	4212	4726	5188	
5	Annual power consumption by air conditioner	kWh_{el}	12331	12331	12331	12331	12331	
6	Annual power consumption from grid	kWh_{el}	9044	8582	8119	7606	7143	
7	Annual useful power output	kWh_{el}	14097	16079	18061	20264	22246	
8	Annual excess power	kWh_{el}	10809	12329	13849	15538	17058	
9	Annual cooling energy demand	kWh_{th}	36200	36200	36200	36200	36200	
10	Solar fraction-Grid supported	Unit less	0.27	0.30	0.34	0.38	0.42	
11	Solar Fraction- net metering	Unit less	0.88	1.00	1.12	1.26	1.38	
12	Electrical (grid)COP	Unit less	4.00	4.22	4.46	4.76	5.07	
13	Energy savings (Grid supported)	kWh_{el}	3288	3750	4212	4726	5188	
14	Primary energy consumption (Reference)	kWh_{PE}	34254	34254	34254	34254	34254	
15	Primary energy consumption(Grid power)	kWh_{PE}	25122	23838	22554	21127	19843	
16	Primary energy saving(Grid supported)	kWh_{PE}	9132	10416	11700	13127	14411	
17	Primary energy saving %(grid supported)	Unit less	27	30	34	38	42	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	130	130	130	131	131	
19	Total investment cost	INR	908436	965873	1023309	1087127	1144564	500000
20	Annual capital cost	INR	125269	130650	136030	142009	147389	87000
21	Maintenance cost	INR	12187	12846	13505	14237	14896	7500
22	Annual electricity cost (Grid supported)	INR	68282	64791	61301	57423	53932	93102
23	Total Annual cost	INR	205737	208287	210836	213668	216217	187602
24	Annual operation and maintenance cost	INR	80468	77637	74805	71659	68828	100602
25	Annual extra cost of solar system	INR	18135	20685	23234	26066	28615	
26	Cost per unit of primary energy saved	INR	1.99	1.99	1.99	1.99	1.99	
27	Payback time (Grid supported)	Years	20.29	20.29	20.29	20.29	20.29	
28	Cost of electricity generated by PV -net metering	INR	106430	121397	136364	152993	167960	
29	Cost of maintenance-net metering	INR	4084	4659	5233	5871	6446	
30	Payback-net metering	Years	4.01	4.01	4.01	4.01	4.01	

Appendix: C – Fresh air Requirements through ventilation

The fresh air requirement is determined by the ventilation rate procedure described in ASHRAE 62.1-2004. This is a prescriptive procedure in which outdoor air intakes rates are determined based on space type/ application, occupancy level and floor area.

1. Breathing Zone Outdoor Airflow: The design outdoor airflow required in breathing zone of the occupiable space or spaces in a zone i.e. the breathing zone outdoor airflow (V_{bz}) shall be determined with equation B-1.

   $$V_{bz} = R_p P_z + R_a A_z \quad \text{B-1}$$

   Where: A_z = zone floor area: the net occupiable floor area of the zone m^2.

   P_z = zone population: the largest number of people expected to occupy the zone during typical usage.

   R_p = outdoor airflow rate required per person as determined from Table 6-1 of ASHRAE 62.1.2004.

   R_a = outdoor airflow requirement per unit area as determined from Table 6-1 of ASHRAE 62.1.2004

2. Zone air distribution effectiveness: The zone air distribution effectiveness (E_z) determined from Table 6-2 of ASHRAE 62.1.2004.

3. Zone Outdoor airflow: The design zone outdoor airflow (V_{oz}), i.e. the outdoor airflow must be provided to the zone by the supply air distribution system. This is given by

   $$V_{oz} = \frac{V_{bz}}{E_z} \quad \text{B-2}$$

4. For Multi zone system: The total outdoor airflow requirement is given by:

   $$V_{ot} = \Sigma_{all\ zones} V_{oz} \quad \text{B-3}$$

For Core Zone:

R_p = 5 cfm/person　　P_z = 8 person

R_a= 0.06 cfm/ ft^2　　A_z = 654 ft^2

E_z = 0.8 (zone air distribution effectiveness)

V_{bz} = (5 x 8) + (0.06 x 654) = 79.27 cfm

V_{oz} = 79.27/0.8 = 99 cfm

ACH = (99 x 60)/ 7848 (volume of zone) = 0.73

Appendix: D– Constuction Material Properties

S.No.	Material	Thermal conducity (kJ/hmK)	Specific heat capacity (kJ/kg K)	Density (kg/m^3)
1	Brick	0.9	1	750
2	Conc Slab	4.068	1	1400
3	Common plaster	1.26	0.84	1200
4	Insulation	0.11	0.1	40

Appendix: E –Calculation of Primary Energy Conversion Factor

The total installed capacity in India as on 31.03.2014[173].

<table>
<tr><th>S. No.</th><th>Type</th><th colspan="2">Insttalled Capacity (GW)</th><th>Actual Power Generation(GWh)2013-14[173]</th><th>Efficiency [174]</th><th>Equivqlent P.E (GWh)</th></tr>
<tr><td>1</td><td>Thermal</td><td colspan="2">168.25</td><td>853683</td><td>0.36</td><td>2371342</td></tr>
<tr><td>2</td><td>Hydro</td><td colspan="2">40.53</td><td>134731</td><td>0.43</td><td>313328</td></tr>
<tr><td>3</td><td>Nuclear</td><td colspan="2">4.78</td><td>34200</td><td>0.80</td><td>42750</td></tr>
<tr><td rowspan="5">4</td><td rowspan="5">New and Renewable</td><td rowspan="5">31.69</td><td>12.66 % Biomass</td><td rowspan="5">53072*
[36]</td><td rowspan="5">0.25</td><td rowspan="5">212288</td></tr>
<tr><td>0.34% Waste to energy</td></tr>
<tr><td>66.69% Wind</td></tr>
<tr><td>12% Small hydro</td></tr>
<tr><td>8.30% Solar</td></tr>
<tr><td></td><td>Total</td><td colspan="2">245.25</td><td>1075686</td><td></td><td>2939708</td></tr>
</table>

* projected from previous year data

$$\text{Primary Energy Conversion Factor} = \frac{1075686}{2939708} = 0.365$$

Appendix: F-1-8 Solar Photovoltaic Cooling System (Single and double axis tracking system) - Energy and cost performance sheet

F-1 Hot and dry climate (Ahmedabad) – Monocrystalline PV cells- Single Axis Tracking

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	22594	25747	28900	32052	35205	
4	Annual power to load	kWh_{el}	6271	7146	8021	8895	9753	
5	Annual power consumption by air conditioner	kWh_{el}	15619	15619	15619	15619	15619	
6	Annual power consumption from grid	kWh_{el}	9348	8473	7598	6723	5865	
7	Annual useful power output	kWh_{el}	21465	24460	27455	30450	33445	
8	Annual excess power	kWh_{el}	15194	17314	19434	21554	23691	
9	Annual cooling energy demand	kWh_{th}	44650	44650	44650	44650	44650	
10	Solar fraction-Grid supported	Unit less	0.40	0.46	0.51	0.57	0.62	
11	Solar Fraction- net metering	Unit less	1.374291	1.566053	1.75781	1.94958	2.141338	
12	Electrical (grid)COP	Unit less	4.78	5.27	5.88	6.64	7.61	
13	Energy savings (Grid supported)	kWh_{el}	6270.82	7145.81	8020.81	8895.41	9753.41	
14	Primary energy consumption (Reference)	kWh_{PE}	43385.20	43385.20	43385.20	43385.20	43385.20	
15	Primary energy consumption(Grid power)	kWh_{PE}	25966.27	23535.72	21105.17	18675.71	16292.38	
16	Primary energy saving(Grid supported)	kWh_{PE}	17418.93	19849.48	22280.03	24709.49	27092.82	
17	Primary energy saving %(grid supported)	Unit less	40.15	45.75	51.35	56.95	62.45	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	249	248	248	247	246	
19	Total investment cost	INR	1688168	1856188	2024208	2192228	2360248	500000
20	Capital cost	INR	198314	214053	229793	245533	261273	87000
21	Maintenance cost	INR	20136	21923	23710	25497	27284	7500
22	Annual electricity cost (Grid supported)	INR	70576	63970	57364	50761	44283	117921
23	Total Annual cost	INR	289026	299946	310867	321791	332839	212421
24	Annual operation and maintainance cost	INR	90712	85893	81074	76257	71566	125421
25	Annual extra cost of solar system	INR	76604.89	87525.45	98446.02	#########	#########	
26	Cost per unit of primary energy saved	INR	4.40	4.41	4.42	4.43	4.44	
27	Payback time (Grid supported)	Years	34.23	34.31	34.37	34.42	34.54	

F-2 Hot and dry climate (Ahmedabad) – Monocrystalline PV cells-Double Axis Tracking

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	24740	28192	31644	35096	38548	
4	Annual power to load	kWh_{el}	6619	7542	8465	9383	10254	
5	Annual power consumption by air conditioner	kWh_{el}	15619	15619	15619	15619	15619	
6	Annual power consumption from grid	kWh_{el}	9000	8076	7154	6235	5365	
7	Annual useful power output	kWh_{el}	23503	26783	30062	33341	36621	
8	Annual excess power	kWh_{el}	16884	19240	21597	23958	26367	
9	Annual cooling energy demand	kWh_{th}	44650	44650	44650	44650	44650	
10	Solar fraction-Grid supported	Unit less	0.42	0.48	0.54	0.60	0.66	
11	Solar Fraction- net metering	Unit less	1.50	1.71	1.92	2.13	2.34	
12	Electrical (grid)COP	Unit less	4.96	5.53	6.24	7.16	8.32	
13	Energy savings (Grid supported)	kWh_{el}	6619	7542	8465	9383	10254	
14	Primary energy consumption (Reference)	kWh_{PE}	43385	43385	43385	43385	43385	
15	Primary energy consumption(Grid power)	kWh_{PE}	25000	22435	19871	17320	14902	
16	Primary energy saving(Grid supported)	kWh_{PE}	18385	20951	23514	26065	28483	
17	Primary energy saving %(grid supported)	Unit less	42	48	54	60	66	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	263	262	261	261	259	
19	Total investment cost	INR	2211427	2425627	2639827	2854027	3068227	500000
20	Capital cost	INR	263399	283465	303531	323597	343663	87000
21	Maintenance cost	INR	26574	28852	31130	33408	35686	7500
22	Annual electricity cost (Grid supported)	INR	67950	60977	54009	47076	40504	117921
23	Total Annual cost	INR	357923	373294	388670	404081	419853	212421
24	Annual operation and maintainance cost	INR	94524	89829	85139	80484	76190	125421
25	Annual extra cost of solar system	INR	145502	160873	176249	191660	207432	
26	Cost per unit of primary energy saved	INR	7.91	7.68	7.50	7.35	7.28	
27	Payback time (Grid supported)	Years	55.39	54.10	53.12	52.39	52.17	

F-3 Moderate climate (Bangalore) – Monocrystalline PV cells -Single Axis Tracking

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	20827	23733	26639	29545	32451	
4	Annual power to load	kWh_{el}	4839	5354	5697	5929	6098	
5	Annual power consumption by air conditioner	kWh_{el}	9887	9887	9887	9887	9887	
6	Annual power consumption from grid	kWh_{el}	5048	4533	4190	3958	3790	
7	Annual useful power output	kWh_{el}	19786	22546	25307	28068	30829	
8	Annual excess power	kWh_{el}	14946	17192	19610	22139	24731	
9	Annual cooling energy demand	kWh_{th}	30060	30060	30060	30060	30060	
10	Solar fraction-Grid supported	Unit less	0.49	0.54	0.58	0.60	0.62	
11	Solar Fraction- net metering	Unit less	2.00	2.28	2.56	2.84	3.12	
12	Electrical (grid)COP	Unit less	5.95	6.63	7.17	7.59	7.93	
13	Energy savings (Grid supported)	kWh_{el}	4839	5354	5697	5929	6098	
14	Primary energy consumption (Reference)	kWh_{PE}	27465	27465	27465	27465	27465	
15	Primary energy consumption(Grid power)	kWh_{PE}	14023	12591	11639	10994	10527	
16	Primary energy saving(Grid supported)	kWh_{PE}	13442	14873	15826	16470	16938	
17	Primary energy saving %(grid supported)	Unit less	49	54	58	60	62	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	192	186	176	165	154	
19	Total investment cost	INR	1688168	2038689	2229522	2420355	2611187	350000
20	Capital cost	INR	198314	231150	249027	266904	284781	60900
21	Maintenance cost	INR	20136	23864	25893	27923	29952	5250
22	Annual electricity cost (Grid supported)	INR	38114	34224	31635	29882	28612	74179
23	Total Annual cost	INR	256563	289237	306555	324709	343345	140329
24	Annual operation and maintainance cost	INR	58250	58087	57528	57805	58565	79429
25	Annual extra cost of solar system	INR	116231	148905	166223	184377	203013	
26	Cost per unit of primary energy saved	INR	8.65	10.01	10.50	11.19	11.99	
27	Payback time (Grid supported)	Years	63.17	79.12	85.81	95.73	108.36	

F-4 Moderate climate (Bangalore) – Monocrystalline PV cells -DoubleAxis Tracking

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	22991	26198	29406	32614	35822	
4	Annual power to load	kWh_{el}	5189	5695	6020	6234	6383	
5	Annual power consumption by air conditioner	kWh_{el}	9887	9887	9887	9887	9887	
6	Annual power consumption from grid	kWh_{el}	4699	4193	3868	3653	3505	
7	Annual useful power output	kWh_{el}	21841	24889	27936	30984	34031	
8	Annual excess power	kWh_{el}	16652	19194	21916	24750	27649	
9	Annual cooling energy demand	kWh_{th}	30060	30060	30060	30060	30060	
10	Solar fraction-Grid supported	Unit less	0.52	0.58	0.61	0.63	0.65	
11	Solar Fraction- net metering	Unit less	2.21	2.52	2.83	3.13	3.44	
12	Electrical (grid)COP	Unit less	6.40	7.17	7.77	8.23	8.58	
13	Energy savings (Grid supported)	kWh_{el}	5189	5695	6020	6234	6383	
14	Primary energy consumption (Reference)	kWh_{PE}	27465	27465	27465	27465	27465	
15	Primary energy consumption(Grid power)	kWh_{PE}	13052	11646	10743	10148	9735	
16	Primary energy saving(Grid supported)	kWh_{PE}	14413	15818	16721	17316	17730	
17	Primary energy saving %(grid supported)	Unit less	52	58	61	63	65	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	206	198	186	173	161	
19	Total investment cost	INR	2211427	2425627	2639827	2854027	3068227	350000
20	Capital cost	INR	263399	283465	303531	323597	343663	60900
21	Maintenance cost	INR	26574	28852	31130	33408	35686	5250
22	Annual electricity cost (Grid supported)	INR	35475	31655	29200	27583	26459	74179
23	Total Annual cost	INR	325448	343972	363861	384588	405808	140329
24	Annual operation and maintainance cost	INR	62049	60507	60330	60991	62145	79429
25	Annual extra cost of solar system	INR	185116	203640	223529	244256	265476	
26	Cost per unit of primary energy saved	INR	12.84	12.87	13.37	14.11	14.97	
27	Payback time (Grid supported)	Years	107.08	109.67	119.88	135.79	157.24	

F-5 Warm and humid climate (Chennai) – Monocrystalline PV cells Single Axis Tracking

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	18582	21175	23768	26361	28954	
4	Annual power to load	kWh_{el}	5927	6754	7581	8408	9235	
5	Annual power consumption by air conditioner	kWh_{el}	17913	17913	17913	17913	17913	
6	Annual power consumption from grid	kWh_{el}	11986	11159	10332	9505	8678	
7	Annual useful power output	kWh_{el}	17653	20117	22580	25043	27506	
8	Annual excess power	kWh_{el}	11727	13363	14999	16635	18272	
9	Annual cooling energy demand	kWh_{th}	51220	51220	51220	51220	51220	
10	Solar fraction-Grid supported	Unit less	0.33	0.38	0.42	0.47	0.52	
11	Solar Fraction- net metering	Unit less	0.99	1.12	1.26	1.40	1.54	
12	Electrical (grid)COP	Unit less	4.27	4.59	4.96	5.39	5.90	
13	Energy savings (Grid supported)	kWh_{el}	5927	6754	7581	8408	9235	
14	Primary energy consumption (Reference)	kWh_{PE}	49758	49758	49758	49758	49758	
15	Primary energy consumption(Grid power)	kWh_{PE}	33295	30998	28700	26403	24106	
16	Primary energy saving(Grid supported)	kWh_{PE}	16463	18760	21058	23355	25652	
17	Primary energy saving %(grid supported)	Unit less	33	38	42	47	52	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	235	235	234	234	233	
19	Total investment cost	INR	1688168	######	2024208	2192228	2360248	500000
20	Capital cost	INR	198314	214053	229793	245533	261273	87000
21	Maintenance cost	INR	20136	21923	23710	25497	27284	7500
22	Annual electricity cost (Grid supported)	INR	90495	84251	78008	71764	65521	135242
23	Total Annual cost	INR	308945	320228	331511	342794	354078	229742
24	Annual operation and maintainance cost	INR	110631	106174	101717	97261	92805	142742
25	Annual extra cost of solar system	INR	79203	90486	101769	113052	124336	
26	Cost per unit of primary energy saved	INR	4.81	4.82	4.83	4.84	4.85	
27	Payback time (Grid supported)	Years	37.00	37.09	37.15	37.21	37.25	

F-6 Warm and humid climate (Chennai) – Monocrystalline PV cells Double Axis Tracking

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	20243	23068	25892	28717	31542	
4	Annual power to load	kWh_{el}	6210	7077	7943	8810	9672	
5	Annual power consumption by air conditioner	kWh_{el}	17913	17913	17913	17913	17913	
6	Annual power consumption from grid	kWh_{el}	11703	10836	9970	9103	8241	
7	Annual useful power output	kWh_{el}	19231	21914	24598	27281	29965	
8	Annual excess power	kWh_{el}	13021	14838	16655	18471	20293	
9	Annual cooling energy demand	kWh_{th}	51220	51220	51220	51220	51220	
10	Solar fraction-Grid supported	Unit less	0.35	0.40	0.44	0.49	0.54	
11	Solar Fraction- net metering	Unit less	1.07	1.22	1.37	1.52	1.67	
12	Electrical (grid)COP	Unit less	4.38	4.73	5.14	5.63	6.22	
13	Energy savings (Grid supported)	kWh_{el}	6210	7077	7943	8810	9672	
14	Primary energy consumption (Reference)	kWh_{PE}	49758	49758	49758	49758	49758	
15	Primary energy consumption(Grid power)	kWh_{PE}	32508	30101	27694	25287	22893	
16	Primary energy saving(Grid supported)	kWh_{PE}	17250	19657	22064	24471	26865	
17	Primary energy saving %(grid supported)	Unit less	35	40	44	49	54	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	246	246	245	245	244	
19	Total investment cost	INR	2211427	######	2639827	2854027	3068227	500000
20	Capital cost	INR	263399	283465	303531	323597	343663	87000
21	Maintenance cost	INR	26574	28852	31130	33408	35686	7500
22	Annual electricity cost (Grid supported)	INR	88356	81814	75271	68729	62222	135242
23	Total Annual cost	INR	378329	394130	409932	425734	441571	229742
24	Annual operation and maintainance cost	INR	114930	110666	106401	102137	97908	142742
25	Annual extra cost of solar system	INR	148587	164388	180190	195992	211829	
26	Cost per unit of primary energy saved	INR	8.61	8.36	8.17	8.01	7.88	
27	Payback time (Grid supported)	Years	61.54	60.03	58.88	57.97	57.28	

F-7 Composite Climate (Delhi) –Monocrystalline PV cells Single Axis Tracking

S.No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	21914	24972	28030	31088	34145	
4	Annual power to load	kWh_{el}	4745	5407	6069	6731	7377	
5	Annual power consumption by air conditioner	kWh_{el}	12331	12331	12331	12331	12331	
6	Annual power consumption from grid	kWh_{el}	7586	6924	6262	5601	4954	
7	Annual useful power output	kWh_{el}	20819	23723	26628	29533	32438	
8	Annual excess power	kWh_{el}	16073	18316	20559	22802	25061	
9	Annual cooling energy demand	kWh_{th}	36200	36200	36200	36200	36200	
10	Solar fraction-Grid supported	Unit less	0.38	0.44	0.49	0.55	0.60	
11	Solar Fraction- net metering	Unit less	1.69	1.92	2.16	2.39	2.63	
12	Electrical (grid)COP	Unit less	4.77	5.23	5.78	6.46	7.31	
13	Energy savings (Grid supported)	kWh_{el}	4745	5407	6069	6731	7377	
14	Primary energy consumption (Reference)	kWh_{PE}	34254	34254	34254	34254	34254	
15	Primary energy consumption(Grid power)	kWh_{PE}	21073	19234	17395	15557	13761	
16	Primary energy saving(Grid supported)	kWh_{PE}	13181	15020	16859	18697	20493	
17	Primary energy saving %(grid supported)	Unit less	38	44	49	55	60	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	188	188	187	187	186	
19	Total investment cost	INR	1688168	1856188	2024208	2192228	2360248	500000
20	Capital cost	INR	198314	214053	229793	245533	261273	87000
21	Maintenance cost	INR	20136	21923	23710	25497	27284	7500
22	Annual electricity cost (Grid supported)	INR	57276	52277	47278	42285	37402	93102
23	Total Annual cost	INR	275726	288254	300782	313315	325959	187602
24	Annual operation and maintainance cost	INR	77412	74200	70988	67782	64686	100602
25	Annual extra cost of solar system	INR	88124	100652	113180	125713	138357	
26	Cost per unit of primary energy saved	INR	6.69	6.70	6.71	6.72	6.75	
27	Payback time (Grid supported)	Years	51.24	51.37	51.47	51.56	51.79	

F-8 Composite Climate (Delhi) –Monocrystalline PV cells Double Axis Tracking

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	23568	26856	30145	33433	36722	
4	Annual power to load	kWh_{el}	4874	5554	6234	6911	7565	
5	Annual power consumption by air conditioner	kWh_{el}	12331	12331	12331	12331	12331	
6	Annual power consumption from grid	kWh_{el}	7458	6778	6098	5421	4767	
7	Annual useful power output	kWh_{el}	22389	25514	28638	31762	34886	
8	Annual excess power	kWh_{el}	17516	19960	22404	24851	27321	
9	Annual cooling energy demand	kWh_{th}	36200	36200	36200	36200	36200	
10	Solar fraction-Grid supported	Unit less	0.40	0.45	0.51	0.56	0.61	
11	Solar Fraction- net metering	Unit less	1.82	2.07	2.32	2.58	2.83	
12	Electrical (grid)COP	Unit less	4.85	5.34	5.94	6.68	7.59	
13	Energy savings (Grid supported)	kWh_{el}	4874	5554	6234	6911	7565	
14	Primary energy consumption (Reference)	kWh_{PE}	34254	34254	34254	34254	34254	
15	Primary energy consumption(Grid power)	kWh_{PE}	20716	18827	16938	15058	13241	
16	Primary energy saving(Grid supported)	kWh_{PE}	13538	15427	17316	19196	21013	
17	Primary energy saving %(grid supported)	Unit less	40	45	51	56	61	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	193	193	192	192	191	
19	Total investment cost	INR	2211427	2425627	2639827	2854027	3068227	500000
20	Capital cost	INR	263399	283465	303531	323597	343663	87000
21	Maintenance cost	INR	26574	28852	31130	33408	35686	7500
22	Annual electricity cost (Grid supported)	INR	56306	51171	46037	40927	35988	93102
23	Total Annual cost	INR	346279	363488	380698	397932	415337	187602
24	Annual operation and maintainance cost	INR	82880	80023	77167	74335	71674	100602
25	Annual extra cost of solar system	INR	158677	175886	193096	210330	227735	
26	Cost per unit of primary energy saved	INR	11.72	11.40	11.15	10.96	10.84	
27	Payback time (Grid supported)	Years	96.57	93.57	91.31	89.62	88.78	

Appendix: G1-4 Solar Photovoltaic Cooling System (VRF) - Energy and cost performance sheet

G-1 Hot and dry climate (Ahmedabad) – VRF

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	18539	21126	23714	26300	28887	
4	Annual power to load	kWh_{el}	10045	10813	11498	11993	12338	
5	Annual power consumption by air conditioner	kWh_{el}	13863	13863	13863	13863	13863	
6	Annual power consumption from grid	kWh_{el}	3818	3050	2365	1870	1525	
7	Annual useful power output	kWh_{el}	18539	21126	23714	26300	28887	
8	Annual excess power	kWh_{el}	8494	10313	12216	14307	16549	
9	Annual cooling energy demand	kWh_{th}	44650	44650	44650	44650	44650	
10	Solar fraction-Grid supported	Unit less	72.46	78.00	82.94	86.51	89.00	
11	Solar Fraction- net metering	Unit less	1.3373007	1.5239126	1.7105966	1.8971363	2.0837481	
12	Electrical (grid)COP	Unit less	11.70	14.64	18.88	23.88	29.28	
13	Energy savings (Grid supported)	kWh_{el}	10045.13	10813.14	11497.97	11992.88	12338.07	
14	Primary energy consumption (Reference)	kWh_{PE}	38508.33	38508.33	38508.33	38508.33	38508.33	
15	Primary energy consumption(Grid power)	kWh_{PE}	10605.20	8471.83	6569.52	5194.77	4235.92	
16	Primary energy saving(Grid supported)	kWh_{PE}	27903.14	30036.50	31938.81	33313.56	34272.42	
17	Primary energy saving %(grid supported)	Unit less	72.46	78.00	82.94	86.51	89.00	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	399	375	355	333	312	
19	Total investment cost	INR	1440309	1529655	1619000	1708345	1797691	500000
20	Capital cost	INR	199195	207565	215935	224305	232674	87000
21	Maintenance cost	INR	19347	20372	21398	22423	23448	12000
22	Annual electricity cost (Grid supported)	INR	28825	23026	17856	14119	11513	117921
23	Total Annual cost	INR	247367	250964	255188	260847	267635	212421
24	Annual operation and maintainance cost	INR	48172	43399	39253	36542	34961	125421
25	Annual extra cost of solar system	INR	34946.24	38542.72	42767.19	48425.58	55214.36	
26	Cost per unit of primary energy saved	INR	1.25	1.28	1.34	1.45	1.61	
27	Payback time (Grid supported)	Years	12.17	12.55	12.99	13.60	14.35	

G-2 Moderate climate (Bangalore) – VRF

S. No	Parameter	Unit	Value					Reference
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	17967	19639	22982	25489	27996	
4	Annual power to load	kWh_{el}	6352	6440	6563	6631	6687	
5	Annual power consumption by air conditioner	kWh_{el}	7048	7048	7048	7048	7048	
6	Annual power consumption from grid	kWh_{el}	696	608	485	417	361	
7	Annual useful power output	kWh_{el}	17967	19639	22982	25489	27996	
8	Annual excess power	kWh_{el}	11615	13199	16419	18858	21309	
9	Annual cooling energy demand	kWh_{th}	30060	30060	30060	30060	30060	
10	Solar fraction-Grid supported	Unit less	90.13	91.37	93.12	94.09	94.88	
11	Solar Fraction- net metering	Unit less	2.5492338	2.7864642	3.2607832	3.6164869	3.9721907	
12	Electrical (grid)COP	Unit less	43.21	49.42	61.99	72.17	83.30	
13	Energy savings (Grid supported)	kWh_{el}	6352.36	6439.76	6563.10	6631.46	6687.14	
14	Primary energy consumption (Reference)	kWh_{PE}	19577.78	19577.78	19577.78	19577.78	19577.78	
15	Primary energy consumption(Grid power)	kWh_{PE}	1932.33	1689.56	1346.95	1157.05	1002.38	
16	Primary energy saving(Grid supported)	kWh_{PE}	17645.45	17888.22	18230.83	18420.73	18575.40	
17	Primary energy saving %(grid supported)	Unit less	90.13	91.37	93.12	94.09	94.88	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	252	224	203	184	169	
19	Total investment cost	INR	1200309	1289655	1379000	1468345	1557691	350000
20	Capital cost	INR	157432	165801	174171	182541	190911	60900
21	Maintenance cost	INR	15747	16772	17798	18823	19848	5250
22	Annual electricity cost (Grid supported)	INR	5252	4592	3661	3145	2724	74179
23	Total Annual cost	INR	178431	187166	195630	204508	213483	140328.75
24	Annual operation and maintainance cost	INR	20999	21365	21459	21968	22572	79429
25	Annual extra cost of solar system	INR	38098.84	46833.96	55297.70	64176.49	73151.07	
26	Cost per unit of primary energy saved	INR	2.16	2.62	3.03	3.48	3.94	
27	Payback time (Grid supported)	Years	14.55	16.18	17.75	19.46	21.24	

G-3Warm and humid climate (Chennai) – VRF

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	16555	18864	21174	23484	25794	
4	Annual power to load	kWh_{el}	9752	10612	11329	11863	12247	
5	Annual power consumption by air conditioner	kWh_{el}	14341	14341	14341	14341	14341	
6	Annual power consumption from grid	kWh_{el}	4589	3729	3012	2478	2094	
7	Annual useful power output	kWh_{el}	16555	18864	21174	23484	25794	
8	Annual excess power	kWh_{el}	6803	8252	9845	11621	13547	
9	Annual cooling energy demand	kWh_{th}	51220	51220	51220	51220	51220	
10	Solar fraction-Grid supported	Unit less	68.00	74.00	79.00	82.72	85.40	
11	Solar Fraction- net metering	Unit less	1.1543825	1.3153894	1.4764661	1.6375427	1.7986193	
12	Electrical (grid)COP	Unit less	11.16	13.74	17.01	20.67	24.46	
13	Energy savings (Grid supported)	kWh_{el}	9751.88	10612.34	11329.39	11862.88	12247.21	
14	Primary energy consumption (Reference)	kWh_{PE}	39836.11	39836.11	39836.11	39836.11	39836.11	
15	Primary energy consumption(Grid power)	kWh_{PE}	12747.56	10357.39	8365.58	6883.68	5816.07	
16	Primary energy saving(Grid supported)	kWh_{PE}	27088.56	29478.72	31470.53	32952.43	34020.04	
17	Primary energy saving %(grid supported)	Unit less	68.00	74.00	79.00	82.72	85.40	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	387	368	350	330	309	
19	Total investment cost	INR	1140309	1229655	1319000	1408345	1497691	500000
20	Capital cost	INR	146991	155361	163730	172100	180470	87000
21	Maintenance cost	INR	14847	15872	16898	17923	18948	7500
22	Annual electricity cost (Grid supported)	INR	34648	28151	22738	18710	15808	135241.97
23	Total Annual cost	INR	196486	199384	203365	208733	215226	229741.97
24	Annual operation and maintainance cost	INR	49495	44024	39635	36633	34756	142741.97
25	Annual extra cost of solar system	INR	-33256.25	-30357.77	-26376.54	-21009.40	-14516.21	
26	Cost per unit of primary energy saved	INR	-1.23	-1.03	-0.84	-0.64	-0.43	
27	Payback time (Grid supported)	Years	10.60	10.93	11.35	11.89	12.54	

G-4 Composite Climate (Delhi) –VRF

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	17096	19482	21867	24253	26639	
4	Annual power to load	kWh_{el}	7640	8175	8602	8949	9222	
5	Annual power consumption by air conditioner	kWh_{el}	10490	10490	10490	10490	10490	
6	Annual power consumption from grid	kWh_{el}	2850	2315	1888	1541	1268	
7	Annual useful power output	kWh_{el}	17096	19482	21867	24253	26639	
8	Annual excess power	kWh_{el}	9456	11307	13265	15304	17417	
9	Annual cooling energy demand	kWh_{th}	36200	36200	36200	36200	36200	
10	Solar fraction-Grid supported	Unit less	72.83	77.93	82.00	85.31	87.91	
11	Solar Fraction- net metering	Unit less	1.6297426	1.8571973	2.0845567	2.3120114	2.5394662	
12	Electrical (grid)COP	Unit less	12.70	15.64	19.17	23.49	28.54	
13	Energy savings (Grid supported)	kWh_{el}	7639.87	8174.86	8601.80	8949.02	9221.76	
14	Primary energy consumption (Reference)	kWh_{PE}	29138.89	29138.89	29138.89	29138.89	29138.89	
15	Primary energy consumption(Grid power)	kWh_{PE}	7917.04	6430.95	5245.00	4280.50	3522.89	
16	Primary energy saving(Grid supported)	kWh_{PE}	21221.85	22707.94	23893.89	24858.39	25616.00	
17	Primary energy saving %(grid supported)	Unit less	72.83	77.93	82.00	85.31	87.91	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	303	284	265	249	233	
19	Total investment cost	INR	1440309	1529655	1619000	1708345	1797691	500000
20	Capital cost	INR	199195	207565	215935	224305	232674	87000
21	Maintenance cost	INR	19347	20372	21398	22423	23448	7500
22	Annual electricity cost (Grid supported)	INR	21519	17479	14256	11634	9575	93102
23	Total Annual cost	INR	240061	245417	251588	258362	265697	187602
24	Annual operation and maintainance cost	INR	40866	37852	35653	34057	33023	100602
25	Annual extra cost of solar system	INR	52458.82	57814.60	63986.14	70759.59	78095.36	
26	Cost per unit of primary energy saved	INR	2.47	2.55	2.68	2.85	3.05	
27	Payback time (Grid supported)	Years	15.74	16.41	17.23	18.16	19.20	

Appendix: H1-4 Solar Photovoltaic Cooling System (Modified Size 7TR) - Energy and cost performance sheet

H-1 Hot and dry climate (Ahmedabad) – 7 TR (24.5 kW)

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	20468	23324	26180	29035	31891	
4	Annual power to load	kWh_{el}	8600	9784	10847	11698	12307	
5	Annual power consumption by air conditioner	kWh_{el}	15561	15561	15561	15561	15561	
6	Annual power consumption from grid	kWh_{el}	6961	5777	4715	3863	3254	
7	Annual useful power output	kWh_{el}	19854	22624	25394	28164	30935	
8	Annual excess power	kWh_{el}	11253	12840	14547	16466	18628	
9	Annual cooling energy demand	kWh_{th}	44650	44650	44650	44650	44650	
10	Solar fraction-Grid supported	Unit less	0.55	0.63	0.70	0.75	0.79	
11	Solar Fraction- net metering	Unit less	1.2758264	1.4538487	1.631871	1.8098933	1.9879155	
12	Electrical (grid)COP	Unit less	6.41	7.73	9.47	11.56	13.72	
13	Energy savings (Grid supported)	kWh_{el}	8600.27	9784.10	10846.83	11698.35	12306.93	
14	Primary energy consumption (Reference)	kWh_{PE}	43226.03	43226.03	43226.03	43226.03	43226.03	
15	Primary energy consumption(Grid power)	kWh_{PE}	19336.40	16047.98	13095.95	10730.60	9040.12	
16	Primary energy saving(Grid supported)	kWh_{PE}	23889.63	27178.06	30130.08	32495.43	34185.92	
17	Primary energy saving %(grid supported)	Unit less	55.27	62.87	69.70	75.18	79.09	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	341	340	335	325	311	
19	Total investment cost	INR	1140309	1229655	1319000	1408345	1497691	500000
20	Capital cost	INR	146991	155361	163730	172100	180470	87000
21	Maintenance cost	INR	14847	15872	16898	17923	18948	7500
22	Annual electricity cost (Grid supported)	INR	52556	43618	35595	29166	24571	117488
23	Total Annual cost	INR	214394	214851	216223	219189	223989	211988
24	Annual operation and maintainance cost	INR	67403	59491	52492	47088	43519	124988
25	Annual extra cost of solar system	INR	1973.24	2430.25	3801.60	6767.54	11567.75	
26	Cost per unit of primary energy saved	INR	0.08	0.09	0.13	0.21	0.34	
27	Payback time (Grid supported)	Years	11.12	11.14	11.30	11.66	12.25	

H-2 Moderate climate (Bangalore) – 5 TR (17.5 kW)

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	30060	30060	30060	30060	30060	
2	PV capacity	kW	70	80	90	100	110	
3	Annual power generation	kWh_{el}	11	12	14	15	17	
4	Annual power to load	kWh_{el}	19772	22531	25204	28048	30807	
5	Annual power consumption by air conditioner	kWh_{el}	8809	9330	9635	9940	10130	
6	Annual power consumption from grid	kWh_{el}	11379	11379	11379	11379	11379	
7	Annual useful power output	kWh_{el}	2570	2050	1744	1439	1249	
8	Annual excess power	kWh_{el}	19179	21855	24448	27207	29883	
9	Annual cooling energy demand	kWh_{th}	10369.124	12525.032	14812.421	17266.326	19752.365	
10	Solar fraction-Grid supported	Unit less	30060.00	30060.00	30060.00	30060.00	30060.00	
11	Solar Fraction- net metering	Unit less	0.7741516	0.8198629	0.8467212	0.8735438	0.890244	
12	Electrical (grid)COP	Unit less	1.69	1.92	2.15	2.39	2.63	
13	Energy savings (Grid supported)	kWh_{el}	11.70	14.66	17.23	20.89	24.07	
14	Primary energy consumption (Reference)	kWh_{PE}	8809.43	9329.60	9635.23	9940.46	10130.50	
15	Primary energy consumption(Grid power)	kWh_{PE}	31609.61	31609.61	31609.61	31609.61	31609.61	
16	Primary energy saving(Grid supported)	kWh_{PE}	7138.98	5694.06	4845.08	3997.23	3469.35	
17	Primary energy saving %(grid supported)	Unit less	24470.63	25915.55	26764.53	27612.38	28140.27	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	77	82	85	87	89	
19	Total investment cost	INR	350	324	297	276	256	
20	Capital cost	INR	990309	1079655	1169000	1258345	1347691	350000
21	Maintenance cost	INR	120889	129258	137628	145998	154368	60900
22	Annual electricity cost (Grid supported)	INR	12597	13622	14648	15673	16698	5250
23	Total Annual cost	INR	19404	15476	13169	10864	9430	85915
24	Annual operation and maintainance cost	INR	152889	158357	165445	172535	180495	152065
25	Annual extra cost of solar system	INR	32000.89	29098.79	27816.44	26537.15	26127.55	91165
26	Cost per unit of primary energy saved	INR	12557.43	18025.10	25112.52	32203.01	40163.18	
27	Payback time (Grid supported)	Years	10.82	11.76	12.93	14.06	15.34	

H-3Warm and humid climate (Chennai) – 7 TR (24.5 kW)

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	17639	20100	22561	25023	27484	
4	Annual power to load	kWh_{el}	9546	10877	12167	13267	14097	
5	Annual power consumption by air conditioner	kWh_{el}	18273	18273	18273	18273	18273	
6	Annual power consumption from grid	kWh_{el}	8727	7397	6107	5006	4176	
7	Annual useful power output	kWh_{el}	17110	19497	21885	24272	26659	
8	Annual excess power	kWh_{el}	7564	8620	9718	11005	12562	
9	Annual cooling energy demand	kWh_{th}	51220	51220	51220	51220	51220	
10	Solar fraction-Grid supported	Unit less	0.52	0.60	0.67	0.73	0.77	
11	Solar Fraction- net metering	Unit less	0.9363248	1.0669748	1.1976247	1.3282747	1.4589247	
12	Electrical (grid)COP	Unit less	5.87	6.92	8.39	10.23	12.26	
13	Energy savings (Grid supported)	kWh_{el}	9545.98	10876.70	12166.68	13267.05	14097.11	
14	Primary energy consumption (Reference)	kWh_{PE}	50759.21	50759.21	50759.21	50759.21	50759.21	
15	Primary energy consumption(Grid power)	kWh_{PE}	24242.60	20546.15	16962.87	13906.29	11600.57	
16	Primary energy saving(Grid supported)	kWh_{PE}	26516.61	30213.07	33796.35	36852.92	39158.64	
17	Primary energy saving %(grid supported)	Unit less	52.24	59.52	66.58	72.60	77.15	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	379	378	376	369	356	
19	Total investment cost	INR	1140309	1229655	1319000	1408345	1497691	500000
20	Capital cost	INR	146991	155361	163730	172100	180470	87000
21	Maintenance cost	INR	14847	15872	16898	17923	18948	7500
22	Annual electricity cost (Grid supported)	INR	65891	55844	46105	37797	31530	137964
23	Total Annual cost	INR	227729	227077	226733	227820	230948	232464
24	Annual operation and maintainance cost	INR	80739	71717	63003	55720	50478	145464
25	Annual extra cost of solar system	INR	-2012.73	-2664.72	-3009.13	-1921.94	1206.06	
26	Cost per unit of primary energy saved	INR	-0.08	-0.09	-0.09	-0.05	0.03	
27	Payback time (Grid supported)	Years	9.89	9.89	9.93	10.12	10.50	

H-4 Composite Climate (Delhi) –7 TR (24.5 kW)

S. No	Parameter	Unit	Value					Reference
1	PV-Area	m^2	70	80	90	100	110	
2	PV capacity	kW	10.75	12.25	13.75	15.25	16.75	
3	Annual power generation	kWh_{el}	19517	22240	24963	27687	30410	
4	Annual power to load	kWh_{el}	6337	7213	8038	8727	9260	
5	Annual power consumption by air conditioner	kWh_{el}	12005	12005	12005	12005	12005	
6	Annual power consumption from grid	kWh_{el}	5668	4792	3967	3278	2745	
7	Annual useful power output	kWh_{el}	18931	21573	24214	26856	29497	
8	Annual excess power	kWh_{el}	12594	14360	16176	18129	20237	
9	Annual cooling energy demand	kWh_{th}	36200	36200	36200	36200	36200	
10	Solar fraction-Grid supported	Unit less	0.53	0.60	0.67	0.73	0.77	
11	Solar Fraction- net metering	Unit less	1.5769652	1.7970069	2.0170486	2.2370902	2.4571319	
12	Electrical (grid)COP	Unit less	6.39	7.55	9.13	11.05	13.19	
13	Energy savings (Grid supported)	kWh_{el}	6337.28	7213.14	8038.03	8727.35	9260.23	
14	Primary energy consumption (Reference)	kWh_{PE}	33346.80	33346.80	33346.80	33346.80	33346.80	
15	Primary energy consumption(Grid power)	kWh_{PE}	15743.25	13310.30	11018.93	9104.17	7623.95	
16	Primary energy saving(Grid supported)	kWh_{PE}	17603.56	20036.50	22327.87	24242.64	25722.85	
17	Primary energy saving %(grid supported)	Unit less	52.79	60.09	66.96	72.70	77.14	
18	Specific primary energy savings(Grid supported)	kWh_{PE}/m^2	251	250	248	242	234	
19	Total investment cost	INR	1140309	1229655	1319000	1408345	1497691	500000
20	Capital cost	INR	146991	155361	163730	172100	180470	87000
21	Maintenance cost	INR	14847	15872	16898	17923	18948	7500
22	Annual electricity cost (Grid supported)	INR	42790	36177	29949	24745	20722	90637
23	Total Annual cost	INR	204628	207410	210577	214768	220140	185137
24	Annual operation and maintainance cost	INR	57637	52050	46847	42668	39670	98137
25	Annual extra cost of solar system	INR	17026.04	19808.25	22975.26	27165.88	32537.62	
26	Cost per unit of primary energy saved	INR	0.97	0.99	1.03	1.12	1.26	
27	Payback time (Grid supported)	Years	15.81	15.83	15.97	16.38	17.06	

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3. B.L.Gupta, Anirudh Batwara, Mayank Bhatanagar, Jyotirmay Mathur "*Effect of panel size on solar photovoltaic refrigeration system*" presented and published in solaris-2012. International conference held at Varansi India.Feb 2012.
4. B.L.Gupta, Mayank Bhatanagar, Jyotirmay Mathur "*Analysis of solar absorption cooling system for domestic applications*" International Journal of Engineering Reasearch and Technology Volume1 issue 9 Nov.2012.
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6. Jyotirmay Mathur, B.L.Gupta, L.M.Gupta,"*Modeling & Simulation of Vapor absorption System using flat plate collector*" Presented and published in the Proceding of International conference on emerging Technologies, Organised by Laxmi Devi Institute of Engineering and Technology Chikani Alwar Raj. 2008.

PROFILE OF THE AUTHOR

Bachchu Lal Gupta was born on 10^{th} Oct, 1979 to sh. Dal chand Gupta and Mrs. Shanti Devi. He passed his bachelor of engineering in Mechanical Engineering in 2001 from M.B.M. Engineering College, Jodhpur. He completed his M. E. (Mechanical Engineering) with specialization in Thermal Engineering from M.B.M. Engineering College, Jodhpur in 2003.

After completing his master degree, he joined teaching profession as lecturer in Mechanical Engineering in Marwar College of Engineering and Research Center (MECRC) Jodhpur in August 2003. After one month later he joined Laxmi Devi Institute of Engineering and Technology, Alwar near to his home town. In March 2004, he got selected in Suratgarh Thermal Power Plants on the post of Junior Engineer that he did not join because he preferred teaching more.

He is presently working as an Assistant Professor and Head Department of Mechanical Engineering in Govt. Engineering College Bharatpur since Aug 2007. He has also served various charges in the present college including Chief Proctor from Aug 2007- Aug 2012. He is a life member of Institute of Engineers and Indian Society of Technical Education. He has been pursuing doctoral studies at Malaviya National Institute of Technology, Jaipur since January 2008.