Modeling and Simulation of Insolation for Solar PV and Thermal Based Power Plants in India

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Dedicated to my wife

Dr. Stellina Jolly

CERTIFICATE

This is to certify that the thesis entitled "Modeling and Simulation of Insolation for Solar PV and Thermal Based Power Plants in India" which is being submitted by Mr. Amit Jain in fulfillment of the requirement for the award of the Degree Doctor of Philosophy in School of Chemistry and Biochemistry, Thapar University, Patiala is a record of candidate's own work carried out by him under our supervision and guidance. The matter in this thesis has not been submitted in part or full to any other university or institution for the award of any degree.

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(Amit Jain)

Abstract

Present research has made recommendations on optimal CSP and PV plant configurations (with respect to solar multiplier, storage, and hybridization), with respect to different solar radiation data sources for India. Present research first lay out arguments for choosing an existing solar resource data set for India based on a number of sources, then applying that data to models that simulate PV and CSP plant configurations at specific locations.

A brief introduction, historical background and the modelling techniques for solar plant design are described. There are several data sources for weather and solar radiation in India. In India, solar resource data is drawn from various sources. These include recently installed state-of-the-art 51 solar meteorological stations throughout the country, Solar Radiation Handbook particularly Solar Radiant Energy over India prepared jointly by IMD and MNRE, the Indian Meteorological Department, National Aeronautics and Space Administration (NASA's) Surface Meteorology and Solar Energy data set, METEONORM's global climatological database, and satellite derived geospatial solar data products from the United States National Renewable Energy Laboratory (NREL), MNRE and IMD joint venture and several satellite based data service providers. One of the major sources of uncertainty in satellite derived solar data as well as ground-measurements is the extensive amount of dust and haze that occurs over India. This can have an impact on the future viability of CSP and PV technologies in India, and impact on plant operations and outputs. Other major challenge in the development of solar power in India is the absence of ground solar radiation data. Impact of Solar PV and thermal power plants in India needs detailed modeling and simulation techniques for design purposes. This thesis embodies the subject matter resulting out of this study.

NASA data and RETScreen software are used to quantify the impact of solar radiation on the technical configuration of different solar PV and thermal plants. Simulation scenarios are run for various sites in India for technical and financial viability of solar power generation with photo-voltaic (PV) technology. RETScreen model is run for various simulation scenarios on the feasibility of sites in India to build a 5 MW PV-grid connected power plant from techno-economical and environmental points of view

are discussed. A model is run for 31 major sites with varied insolation in India to measure the viability of Solar PV plants at these sites. Financial incentives announced in national solar mission of India have also been used as an input to the model. Viability indicators like internal rate of return (IRR), net present value (NPV), cost of electricity (CoE), and benefit cost (B-C) ratio are identified on the basis of the model. A comparison of results is done and the best sites in India are reported.

SAM (SAM, 2011) developed by Sandia laboratories and National Renewable Energy Laboratory (NREL) is used for the weather data, cost estimates, and local specific assumptions. NREL solar radiation data and SAM model have been used for simulations to develop a cost minimization model to investigate the techno-commercial viability of a 100 MW parabolic trough solar thermal plant (PTST) for power generation at different sites in India. Cost minimization model prescreens the solar potential in India on the basis of parameters like slope, direct normal irradiation (DNI), protected areas etc. In order to identify the least costly feasible option for the installation of the PTST, a parametric cost–benefit analysis was carried out by varying parameters, such as capacity factor, capital investment, operating hours, etc. Cost minimization model focuses on the assessment of CSP potential in India based on high resolution NREL satellite DNI data uses SAM to optimize and measure the performance of CSP plants. Preliminary screening of sites is done based on the climate and geographical parameters and 25 sites are shortlisted. Financial incentives announced by government of India have been considered as an input to the model. The proposed model predicts various viability indicators like IRR, NPV, CoE, B-C ratio for 100 MW solar CSP at 25 sites in India. A comparison of the results is done and Jodhpur, Rajkot and Indore are found to be the best sites for setting up of 100 MW solar CSP plant in India. On the basis of the present study, it is recommended to erect the PTST power plant in the western region of India.

The next section investigates the economic and financial feasibility of a 100MW parabolic trough concentrating solar power plant with energy storage at Jodhpur, Rajasthan, India. Base case scenario is defined as a 100 MW plant without thermal energy storage. The resulting Power Purchase Agreement (PPA) price comes out to be 34.17 US cents/kWh, barely within acceptable range of specified feed-in tariff indicated by the Indian Government in Jawaharlal Nehru National Solar Mission (JNNSM). This implies that although the system configuration in the base case may be financially feasible, it yields lower returns. Scenario analysis with varying solar multiples and thermal energy storage has been done in the present study.

In the last section, it is concluded that the lowest PPA price of about 31.4 US cents/kWh can be achieved in a system configuration having a solar multiple of two and equipped with three hours of thermal energy storage system. Sensitivity analysis is done to measure the impact of uncertainty of solar radiation on project economics and performance. The uncertainty in measurement and prediction of solar radiation has a direct impact on the levelized cost of electricity (LCOE) and capacity factor of the 100 MW parabolic trough plant. For the optimal design, six different plant configurations have been compared for an initial analysis. The different plant designs include 2 solar-only plants (differing in solar multiples) without storage or hybridization, two solar-only plants with storage capacity of four and eight hours respectively, and one solar plant integrated with dry cooling technology. Trough plant steam cycle performance is modeled in cost minimization model and SAM using Jodhpur, Rajasthan as the reference site. Hourly net electricity, fossil energy consumption, and ambient temperature are estimated. The total cost for the installation of solar hardware is based on Central Electricity Regulatory Commission (CERC) cost assumptions. The results obtained from the present study provide information to establish technical criteria for the design of CSP plants, which optimizes the solar electricity produced and its generation cost. Based on the present study, it is recommended that CSP projects could include 50-100 MW capacity project with a minimum of four hours of storage, one 100 MW hybrid project with a maximum of 30 % gas fraction and one 20-25 MW project employing 100 % dry cooling technique and minimum water consumption.

Accurate DNI database is the one of the dominant problem in the deisgn and simulation of CSP plants in India. Accuracy to within 5% is currently out of reach of satellite-derived data without additional ground readings. Due to inter-annual variability, 10-20 years of DNI data is needed for project-specific data to reach such accuracy. Although satellite-datasets cover many regions, and can help to identify good sites, most of them are biased, meaning they have significant systematic errors. Thus, although satellite DNI maps can be used for site-selection, these need to be verified by qualified measurements at the project development stage. Since at least one year of measurements are recommended for due diligence, this can slow down development unless a suitable meteorological station is installed as soon as possible. One solution is to use multiple datasets to find a quality-weighted best estimate. This means combining well maintained, calibrated and screened ground-based measurements and qualified time-series satellite data to analyse long-term variability at proposed sites. Also important is the benchmarking of satellite-derived DNI products with sound measurements.

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Abbreviations

BOP	Balance of plant
CERC	Central Electricity Regulatory Commission
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiation
EPC	Engineering, Procurement and Construction
EPW	Energy Plus Weather Files
GAIL	Gas Authority of India Limited
GoR	Government of Rajasthan
GS	Gas Station
GW	Gigawatts
Ha	Hectare
HCE	Heat Collection Element
IGNP	Indira Gandhi Nahar (canal) Project
ISHRAE	Indian Society of Heating, Refrigerating and Air-Conditioning Engineers
JNNSM	Jawaharlal Nehru National Solar Mission
Km	Kilometre
KVA	Kilo Volt Amperes
KW	Kilowatt
kWh	Kilowatt Hour
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
mm	Millimetre
MMSCMD	Million Metric Standard Cubic Feet Per Day
MNRE	Ministry of New and Renewable Energy
MSL	Mean Sea Level
MVA	Mega Volt Amperes
MW	Megawatt

MWh	Megawatt Hour
NAPCC	National Action Plan on Climate Change
NREL	National Renewable Energy Laboratory
ONGC	Oil and Natural Gas Corporation
RSPCL	Rajasthan State Power Corporation Limited
RVUN	Rajasthan Vidyut Utpadan Nigam
SAM	System Advisory Model
SCA	Solar Collector Assembly

Chapter - 1

Introduction and Statement Of Problem Being Addressed

1.1 Background

Resource assessment is the primary and essential exercise towards project evaluation. In renewable energy projects the resource assessment exercise is important because of the intermittent nature of the resource. The maximum possible value of solar radiation on earth is solar constant (i.e. 1367 W/m^2); which is the part of the energy emitted by the sun per unit time intercepted by a unit area of surface perpendicular to the direction of propagation of the radiation at the earth's mean distance from sun outside the atmosphere. Hence this indicates the maximum level of solar radiation available close to the earth, while as experienced on the earth's surface, the intensity of incident solar radiation varies, due to earth's rotation and variation of distance from the sun throughout the year. The solar radiation intensity at any location varies throughout the year due to variation in solar declination angle, solar hour angle and geographical angles like latitude and longitude. Besides these atmospheric conditions, such as humidity, cloud cover, amount of dust in air etc contribute towards attenuation of solar radiation received on the earth's surface.

The solar radiation as received by the earth is classified in two major components. Part of the radiation appears to be coming directly from the sun in direct form; this is known as direct Horizontal irradiation (DHI). It is also responsible for casting sharp shadows, and part of the radiation appears to be coming from any other direction; this radiation is the result of scattering and reflection of solar radiation by surroundings, clouds, dust in air etc. This is known as diffuse radiation. The sum of direct and diffuse radiation is known as global radiation.

The solar radiation arriving at the earth's surface has two components –Direct and Diffuse solar radiation

(Direct / Diffuse) ratio: 0.9 Clear day
0.0 completely overcast day

The total irradiance at any surface is the sum of the two components

H(total) = H (direct on a horizontal surface) +H (diffuse)

Solar irradiance is a measure of the amount of solar energy reaching a surface, or irradiance, on a given surface over time. The surface in question can be anything exposed to sunlight, from a particular object or location on Earth to small space-going objects such as artificial satellites to an entire planet's surface. The solar insolation at a particular area of the Earth depends on its distance from the equator, its weather conditions, and the time of day and year. It is essential to the continued existence of life on Earth, as plants rely on energy from the sun to survive, as well as being an important factor in the construction and location of equipment to generate electricity from solar power.

Usually measured in watts per square meter, the average solar insolation of an area over longer periods of time is often given as kilowatt hours per square meter per day. The watt is the standard metric unit of power, or energy over a specified unit of time; one watt of power is equal to one joule of energy per second. A kilowatt hour, a term most commonly used in reference to electric power generation, is enough energy to produce an output of 1,000 W/hr, or 3,600,000 joules (3.6 MJ).

The more directly a surface faces the sun, the higher its solar insolation will be. Maximum solar insolation is produced when the sun's light strikes at a 90° angle. Insolation decreases as the angle becomes lower, because a lower angle spreads the same amount of radiant energy over a wider area. This is why the area around the Earth's equator, which receives the most direct sunlight, is the warmest part of the Earth and the polar regions are the coldest. It also causes the changing seasons, because the Earth's tilted axis means that the angle of the sunlight reaching a given part of the planet changes in the course of the year. This is also why the temperature on a given day will tend to peak around solar noon, when the sun is at its highest point in the sky, and then decrease as the sun drops closer to the horizon later in the day.

The total solar insolation of the Earth's outer atmosphere from direct sunlight averages about 1,367 W/m^2 at an angle of 90° over the course of a year, the majority of which is in the form of visible light. Attenuation of the sunlight as it passes through the atmosphere reduces this to about 1,000 W/m^2 at an angle of 90° by the time it reaches the Earth's surface. This figure steadily drops as a person moves to higher latitudes and decreases at times of day further from solar noon, dropping to almost nothing at night. The average insolation of the Earth as a whole over the course of a year is around 250 W/m^2.

Areas at similar latitudes can still have significant differences in average insolation due to local factors. An area's insolation can be further decreased by atmospheric conditions that interfere with sunlight, such as clouds or atmospheric haze. Insolation rises at higher altitudes, because there is less atmosphere for the solar radiation to pass through and be attenuated by. Measurements of the amount of solar irradiance at different locations can be compiled to create a specialized map called an insolation map.

Solar power generation relies heavily on insolation. Photovoltaic solar panels are mounted at angles intended to make incoming sunlight strike them at as close to a 90° angle as possible to maximize the power received. The optimal angle for this varies according to the geographic location and the time of year.

The insolation of an area can also be exploited in the design of buildings. For example, large windows on the side of a building facing the equator will let in more light and heat during the winter, when the sun is low in the sky, and comparatively less when it is high in the sky during the summer. This moderates seasonal temperature extremes inside the building, making it more comfortable and reducing the amount of energy needed for heating or air conditioning.

Every location on Earth receives sunlight at least part of the year. The amount of solar radiation that reaches any one spot on the Earth's surface varies according to:

- Geographic location
- Time of day
- Season
- Local landscape
- Local weather.

Because the Earth is round, the sun strikes the surface at different angles, ranging from 0° (just above the horizon) to 90° (directly overhead). When the sun's rays are vertical, the Earth's surface gets all the energy possible. The more slanted the sun's rays are, the longer they travel through the atmosphere, becoming more scattered and diffuse. Because the Earth is round, the frigid polar regions never get a high sun, and because of the tilted axis of rotation, these areas receive no sun at all during part of the year.

The 23.5° tilt in the Earth's axis of rotation is a more significant factor in determining the amount of sunlight striking the Earth at a particular location. Tilting results in longer days in the northern hemisphere from the spring (vernal) equinox to the fall (autumnal) equinox and longer days in the southern hemisphere during the other 6 months. Days and nights are both exactly 12 hours long on the equinoxes, which occur each year on or around March 23 and September 22.

1.2 Solar PV power generation technologies

PV generation technology is commercially proven and large multi-megawatt generation plants have been operating since the 1990s. Costs associated with the technology are high, but the technology is well-known and reliable (Figure 1.1). The largest plants are based on fixed solar panels inclined at latitude angle. Across the world, this has proved to be the most economic way of building PV power stations. More recent developments use PV collectors that track the Sun to allow collection of a greater amount of energy and concentrating photovoltaic (CPV systems that focus the collected solar energy into a smaller area).

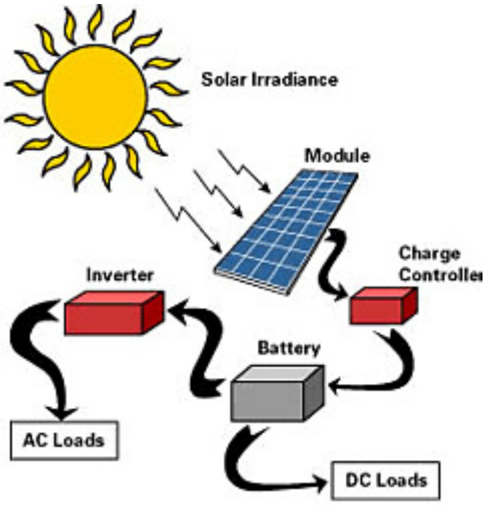

Figure 1.1 Schematic of Solar PV system (New Generation Energy website, 2009)

1.3 Solar thermal power generation technologies

Solar thermal power systems, also known as Concentrating Solar Power (CSP) systems, use concentrated solar radiation as a high temperature energy source to produce electricity using the thermal route. Since the average operating temperature of stationary non-concentrating collectors is low (max up to 120^{o}C) as compared to the desirable input temperatures of heat engines (above 300^{o}C), the concentrating collectors are suitable for high temperature applications. These technologies are appropriate for regions where direct solar radiation is high. The mechanism of conversion of solar energy to electricity is fundamentally similar to the traditional thermal power plants except it uses solar energy as a source of heat. Solar collectors are used to produce heat from solar radiation. However, the three most promising CSP technologies are parabolic trough, central receiver or solar tower, and parabolic dish (ESTIA Report, 2005).

a. Parabolic trough system: Temperature of the receiver can reach 400° C and produces steam for generating electricity. This is conducted along a heat exchanger in which steam is produced, which then generates power in the turbines (European Commission, 2007).

b. Power tower system: The reflected rays of the sun are always aimed at the receiver, where temperatures well above 1000° C can be reached (Figure 1.2).

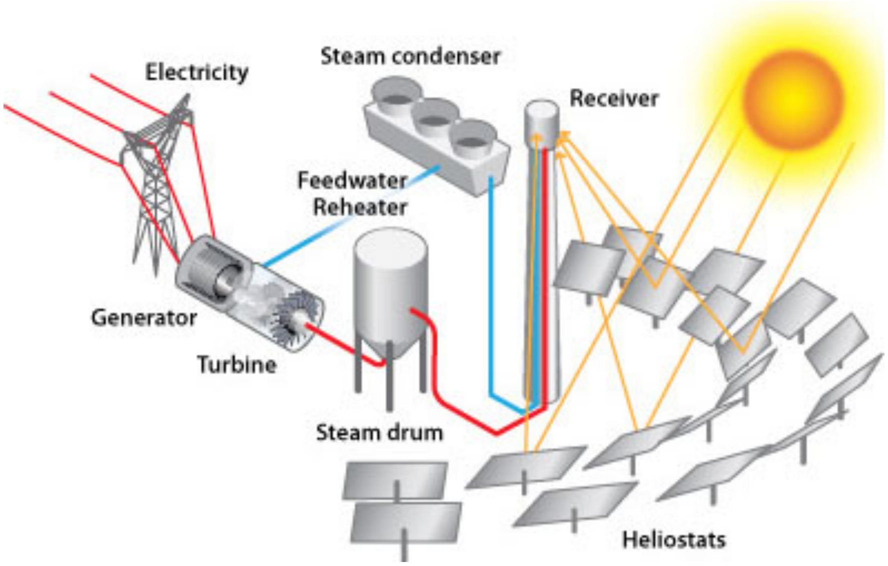

Figure 1.2 Schematic of power tower system (US Department of Energy, 2009)

c. Parabolic dish systems: Parabolic dish systems can reach 1000° C at the receiver, and achieve the highest efficiencies for converting solar energy to electricity (Figure 1.3).

Figure 1.3 Parabolic dish systems (New Fuel Now, 2009)

India is located in the subtropical sun belt of the earth, thereby receiving abundant radiant energy from the sun, equivalent energy potential of which is about 6,000 million GWh of energy per year. In most parts of India, clear sunny weather is experienced 250 to 300 days a year. The annual global radiation varies from 1600 to 2200 kWh/m^2, which is comparable with radiation received in the tropical and sub-tropical regions. Rajasthan, Gujarat, Maharastra, Andhra Pradesh etc. states are located in the best sunny regions of the country. Figure 1.4 presents solar radiation map of India.

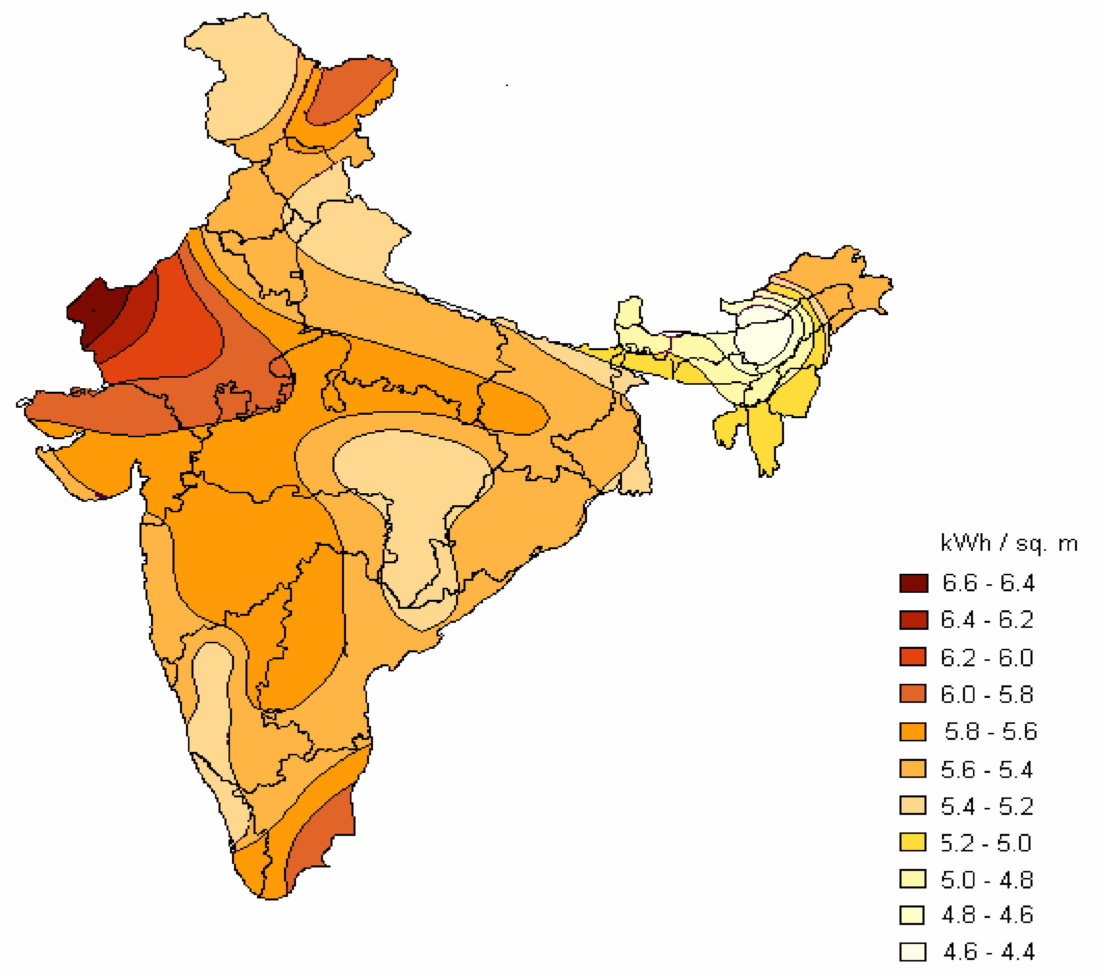

Figure 1.4 Solar radiation map of India (MNRE, 2010)

The cost associated with electrical energy derived from fossil and nuclear fuel, and an increase in environmental regulations continues to constrain the planning and operation of electric utilities. Furthermore, the global economic and political conditions that tend to make countries more dependent on their own energy resources have caused growing interest in the development and use of renewable energy (National Renewable Energy Laboratory, 1996). In terms of its environmental advantages, renewable resources generate electricity with insignificant contribution of carbon dioxide (CO_2) or other greenhouse gases (GHG) to the atmosphere and they produce no pollutant discharge on water or soil (EL-Shimy, 2009).

India is one of the few countries to have a major renewable energy program for nearly two decades, and is the only country to have a full-fledged national ministry to deal with renewable energy. India’s renewable energy program was launched primarily as a response to the professed rural energy crisis in the 1970s, the renewable energy program gained momentum with an economic liberalization program, which began in the early 1990s (Venkata et al., 2001). The emphasis shifted from purely subsidy-driven dissemination program to technology promotion through the commercial route. Despite India being the only country with a dedicated Ministry for New and Renewable Energy (MNRE), and an extensive set of policies, the renewable energy sector is witnessing slow growth. Key reasons for the slow growth include multiplicity of agencies, skewed incentive structure, and poor implementation capability (Subramanian, 2008).

1.4 Advantages of solar energy

Photovoltaic (PV) power systems convert sunlight directly into electricity. A residential PV power system enables a homeowner to generate some or all of its daily electrical energy demand on its own roof, exchanging daytime excess power for future energy needs (i.e. night time usage). The house remains connected to the electric utility at all times, so any power needed above what the solar system can produce is simply drawn from the electric utility. Solar energy technologies can play an important role in providing an alternative source of electricity, energy, and back-up power for homes, offices, and commercial and industrial buildings. It can relieve demand pressures for electricity off from the grid during peak usage, which usually correlates to peak daylight, especially in the warmer months when demand for air conditioning can sky rocket.

Solar energy can also play an important role in lowering greenhouse gas (GHG) emissions by replacing coal-powered energy sources with clean, renewable solar PV technologies. These GHG emissions reductions will in turn improve air quality and lessen the harmful impacts that contribute to climate change.

Infinite Free Energy: Another advantage of using solar energy is that beyond initial installation and maintenance, solar energy is one hundred percent free. Solar doesn’t require expensive and ongoing raw materials like oil or coal, and requires significantly lower operational labor than conventional power production. Lower costs are direct as well as indirect – less staff working at the power plant as the sun and the solar semi conductors do all the work, not to mention no no raw materials need to be extracted, refined, and transported to the power plant.

Decentralization of power: Solar energy offers decentralization in most (sunny) locations, meaning self-reliant societies. Oil, coal, and gas used to produce conventional electricity are often transported cross-country or internationally. This transportation has a myriad of additional costs, including monetary costs, pollution costs of transport, and roading wear and tear costs. These factors are not of a concern with solar. Of course, decentralization has its limits as some locations get more sunlight than others.

Going off the grid with solar: Going off grid is a huge advantage of solar power for people in isolated locations. Solar energy can be produced on or off the grid. On grid means a house remains connected to the state electricity grid. Off grid has no connection to the electricity grid, so the house, business or whatever being powered is relying solely on the solar or solar-hybrid. The ability to produce electricity off the grid is a major advantage of solar energy for people who live in isolated and rural areas. Power prices and the cost of installing power lines are often exorbitantly high in these places and many have frequent power-cuts. Many city-dwellers are also choosing to go off the grid with their alternate energy as part of a self-reliant lifestyle.

Saving eco-systems and livelihoods: Because solar doesn't rely on constantly mining raw materials, it doesn't result in the destruction of forests and eco-systems that occur with most fossil fuel operations. Destruction can come in many forms: from destruction through accepted extraction methods, to more irresponsible practices in vulnerable areas, to accidents. Solar energy systems have very little impact on the environment, making it one of the cleanest power-generating technologies available today. While converting the sun's rays into electricity or hot fluids, it does not produce air pollution, hazardous waste, or noise. The more electricity and heat are converted from the sun's rays, reliance and dependence on fossil fuels and on imported sources of energy decrease. Finally, solar energy can be an effective economic development driver. Solar cells provide cost effective solutions to energy problems in places where there is no means of electricity. Solar cells are also totally silent and non-polluting. As it has no moving parts, it requires little maintenance and has a long lifetime. Compared to other renewable sources, it also possesses many advantages; wind and water power rely on turbines which are noisy, expensive and liable to breaking down.

Rooftop power is a good way of supplying energy to a growing community. More cells can be added to homes and businesses as the community grows so that energy generation is in line with demand. Many large scale systems currently end up over generating to ensure that everyone has enough. Solar cells can also be installed in a distributed fashion, i.e. they don't need large scale installations. Solar cells can easily be installed on roofs, ergo, no new space is needed and each user can quietly generate its own energy.

1.5 Disadvantages of Solar Energy

Solar doesn’t work at night: Obviously the biggest disadvantages of solar energy production revolve around the fact that it’s not constant. To produce solar electricity there must be sunlight. So energy must be stored or sourced elsewhere at night. Beyond daily fluctuations, solar production decreases over winter months when there are less sunlight hours and sun radiation is less intense.

Solar Inefficiency: A very common criticism is that solar energy production is relatively inefficient. Currently, widespread solar panel efficiency – how much of the sun’s energy a solar panel can convert into electrical energy – is at around 22%. This means that a fairly vast amount of surface area is required to produce a lot of electricity. However, efficiency has developed dramatically over the last five years, and solar panel efficiency should continue to rise steadily over the next five years. For the moment though, low efficiency is a relevant disadvantage of solar.

Storing Solar: Solar electricity storage technology has not reached its potential yet. While there are many solar drip feed batteries available, these are currently costly and bulky, and more appropriate to small scale home solar panels than large solar farms.

Solar panels are bulky: Solar panels are bulky. This is particularly true of the higher-efficiency, traditional silicon crystalline wafer solar modules. These are the large solar panels that are covered in glass. New technology thin-film solar modules are much less bulky, and have recently been developed as applications such as solar roof tiles and “amorphous” flexible solar modules. The downfall is that thin-film is currently less efficient than crystalline wafer solar.

One of the biggest disadvantages of solar energy – COST: The main hindrance to solar energy going widespread is the cost of installing solar panels. Capital costs for installing a home solar system or building a solar farm are high. Particularly obstructive is the fact that installing solar panels have large upfront costs – after which the energy trickles in for free. That’s an incredibly disadvantageous feature of solar energy production, particularly during a time of recession.

1.6 Relevance of Solar in India Energy Situation

Energy security is a global issue, especially in the context of global climate change which is caused by historical GHG emissions, largely related to fossilfuel-based energy generation. To fuel the world's economic growth, a substantial amount of energy is needed. Given the demand, it is also noted that planning and operation of electricity utilities are constrained by the increasing cost associated with non-renewable energy sources and global awareness of climate change and the environment (El-Shimy, 2009).

With over 15% of world's population and a high-growth economy, India has become a significant consumer of energy resources. According to India's Central Electricity Authority (CEA) (2009), the country's per capita electricity consumption rose from merely 15.6 kWh in 1950 to 592 kWh in 2003 - 2004, reaching 717 kWh in 2007 – 2008. The average per capita consumption is expected to surpass 1,000 kWh by 2011-12. The country's installed power generation capacity was 180,358 MW as of 2011 (Energy Information Administration, 2011). Accordingly, the Energy Information Administration (2011) states that in 2011, over 75% of energy in India is derived from conventional thermal sources such as coal (53.75 %), oil (0.70 %) and natural gas (10.30 %) The total demand for electricity continues to rise, outpacing increases in capacity. In fact, India is suffering from a severe shortage of electricity which is hindering its economic growth and improvement in its standard of living. The World Bank reported that about 40% of residences in India are without electricity (Energy Information Administration, 2011). Blackouts are common throughout the country's main cities. CEA has projected that in the current financial year (2011-12), there will be an overall energy shortfall of 10.3%, and a peak shortage of 12.9% in the country (India Energy Portal, 2011).

India has tremendous renewable energy potential. It has about 20.6 GW of installed renewable power generation capacity, which is around 11% of the country's total power generation capacity, contributing over 4% in the electricity mix for 2011. The country's potential for renewable energy in the year 2032 is projected to be 220 GW (KPMG, 2011). Wind capacity captures the largest share (70 %) at over 14 GW, followed by small hydro (SHP) capacity at 3 GW, while biomass-based power systems account for another 2.9 MW of capacity.

Although the country is blessed with abundant solar energy resources, the share of solar energy in the renewable energy mix is relatively small. With an average intensity of solar radiation of four to seven KWhr/m^2/day, the available solar energy in the country is approximately eight million MW, equivalent to 5,909 million tons of oil equivalent (MTOE) per year (India Energy Portal, 2010). Given the potential, solar contributed only about 825 kW of renewable energy capacity in 2006 (Meisen and Queneudec, 2006) and 481.5 MW till January 2012 (MNRE, 2011), falling far behind wind, small hydro, and biomass energy (Amulya, 2009). It is believed that concentrating on solar thermal systems are more cost-effective than photovoltaic systems (Quanschning, 2004). As the government targets 20,000 MW of solar power by the year 2022 as a part of the JNNSM (MNRE, 2011), solar energy is identified as a viable option to reduce the supply-and-demand gap, making solar power plants – and eventually, solar thermal power plants –a huge potential for development in the country.

In the first phase of JNNSM, one GW of grid-connected solar is targeted for 2013, with an approximate 50:50 split between CSP and photovoltaic (PV) technologies. A total of seven CSP projects, worth 470 MW, have been selected in the Phase 1 of JNNSM. In the first phase of the program, the lending community is having concerns related to technology risk, power off-take and payment security. JNNSM model of setting a maximum tariff and inviting reverse auction by bidders, have advantages as well as risks. Timelines for obtaining financial closure, construction and commissioning demanded under Phase 1 of JNNSM are some of the challenges CSP projects are facing (KPMG, 2011). An important consideration should be including technical and business capabilities as criteria, as well as low cost in the selection process for the next phases of JNNSM.

MNRE's plans of setting up CSP demonstration projects using technologies that are not covered under commercial projects is one of the windows envisaged to attain the mission of making solar power cost effective, and to achieve parity with grid power by 2022. For this, it is anticipated/envisaged to have advanced technology configurations including hybridization, dry cooling and storage technologies, which could lead to cost reduction through higher efficiency, capacity utilization factor (CUF), and scale effect (MNRE, 2011).

There are also state specific market factors to be considered in regions identified as most favorable for CSP systems, such as Gujarat and Rajasthan. The 2003 Electricity Act requires State Electricity Regulatory Commissions (SERCs) to specify a minimum Renewable Purchase Obligation (RPO) and allow for preferential renewable tariffs to be established (Ministry of Law and Justice of India, 2003). The RPO for each state varies from a total of 1% to 14%. Some states also include a specific RPO for solar energy. The Gujarat Solar Power Policy 2009 (Government of Gujarat, 2009) specifies a tariff of INR 10 / kWh (22 US cents/kWh) for the first 12 years, and INR

3 / kWh (6.7 US cents/kWh) for years 13 to 15, for CSP projects built before 31 December 2012. The Government of Rajasthan (2011) followed suit with the release of Solar Policy 2011, which foreshadows a tariff based bidding process similar to JNNSM.

1.7 Statement of Problem Being Addressed

Detailed solar and weather condition assessments are necessary to understand project economics for solar power systems. In Solar PV plants for example, the plant's operating capacity is highly sensitive to GHI and the consequent bearing on the project cost is significant. For a given MW capacity, the GHI will determine the plant size (number of panels required, land requirement etc.), capacity factor and plant costs. A change in GHI directly impacts the electricity production and in turn, the revenues realized. It is to be noted that understanding the project costs and returns after accounting for the impact of solar radiation levels will have an impact on tariff expectations. Similarly, a detailed understanding of DNI is critical for solar thermal systems and consequently it is a critical component of the technical analysis for the development of the solar. The dependence of project risks and returns on the solar resource availability at a particular site will also impact lender's perception of these projects and affect overall bankability.

The significant impact that measurements of solar radiation and climatic conditions will have on a solar power projects has led investors and project developers to stress the importance of gathering detailed information for potential sites. Ideally, on the ground measurements should be collected over a period of 10 years. In addition, ground measurements should be compared and correlated to satellite based analyses to present a comprehensive understanding to project stakeholders. Thus measured data will also be used for improving the accuracy of satellite-based modeling of solar radiation and validation of solar resource forecasting methods.

Accurate DNI data is hard to come by and expensive to obtain. But creative solutions could resolve some of the issues currently faced by developers. Concentrated solar power project developers need accurate, 'bankable data' of solar radiation to establish the long-term profitability of projects and to optimise design and processes. But reliable DNI data is proving hard to come by, with developers encountering differences of up to 20-50% in accuracy. A host of issues surround DNI modelling and measuring. Existing measured data, which is routinely collected by meteorological services or universities, can be difficult for developers to access and rarely bears direct relevance to the proposed project site. As such, data collection, which many agree is essential for the selection of CSP/CPV sites, often has to be carried out by the developers themselves.

But obtaining accurate, site-specific measurements is by no means straightforward. Because of the difficulties associated with obtaining reliable and accurate field data, instrumented sites might not be located at the final plant location, meaning some form of spatial extrapolation is required.

Ideally, local radiation measurements should be undertaken over several years to obtain a sense of the long-term DNI resource. However, since most companies are eager to complete financing within a year or so, it is also necessary to find methods of proper time-extrapolation.

Another approach is to use site-specific modelled data, which is collected by obtaining measured data from a nearby station and estimating what the resource might be at other interesting sites in the area. Two further types of modelled data include publicly available and commercial gridded-data. This is gathered using satellite algorithms to infer atmospheric conditions and calculate the down-welling solar irradiation at ground level from radiative transfer modelling. A downside of site-specific modelling is that providers often lack sufficient knowledge of uncertainties at each step of the development process, and may choose the wrong model or data source for the job.

Although satellite-derived DNI products could, in principle, be more accurate than measurements, current accuracy remains poor, mainly due to difficulties in retrieval of atmospheric condition data since all models rely on (often inaccurate) aerosol information. Because models use different sources for clouds and aerosols it is normal to find significant differences in predictions - the exact cause of which, remains elusive. It is clear that absolute accuracy is the dominant problem. Accuracy to within 5% is currently out of reach of satellite-derived data without additional ground readings. Due to inter-annual variability, 10-20 years of DNI data is needed for project-specific data to reach such accuracy.

Although satellite-datasets cover many regions, and can help to identify good sites, most of them are biased, meaning they have significant systematic errors. Unfortunately, bias is not constant between sites and over time. Thus, although satellite DNI maps can be used for site-selection, these need to be verified by qualified measurements at the project development stage. Since at least one year of measurements are recommended for due diligence, this can slow down development unless a suitable meteorological station is installed as soon as possible. One solution is to use multiple datasets to find a quality-weighted best estimate. This means combining well maintained, calibrated and screened ground-based measurements and qualified time-series satellite data to analyse long-term variability at proposed sites. It is difficult to deny that many CSP project developers currently face an uphill struggle in obtaining DNI data accurate enough to underpin a consistently low-risk approach to site-selection. Nevertheless, pragmatic, and relatively low-cost alternatives, combining the strengths of different methodologies, may be within the grasp of those developers prepared to adopt a more flexible and intelligent approach.

Present research has made recommendations on optimal CSP and PV plant configurations (with respect to solar multiplier, storage, and hybridization), with respect to different solar radiation data sources for India. One of the major sources of uncertainty in satellite derived solar data as well as ground measurements is the extensive amount of dust and haze that occurs over India. This can have an impact on the future viability of CSP and PV technologies in India, and impact on plant operations and outputs. Present research first lay out arguments for choosing an existing solar resource data set for India based on a number of sources, then applying that data to models that simulate PV and CSP plant configurations at specific locations.

Chapter - 2

Literature Review

2.1 Introduction to solar radiation concepts

When solar radiation enters the earth’s atmosphere, a part of the incident energy is removed by scattering or absorbing air molecules, clouds and particulate matter usually referred to as aerosols. The radiation that is neither reflected nor scattered reaches the surface straight from the solar disk is called direct or beam radiation. The total radiation consisting of three components – direct, scattered and reflective – are called global or total radiation (MNRE, 2000). Figure 2.1 illustrates the total solar radiation on a horizontal surface, which is the sum of the diffuse plus the direct beam, times the cosine zenith angle.

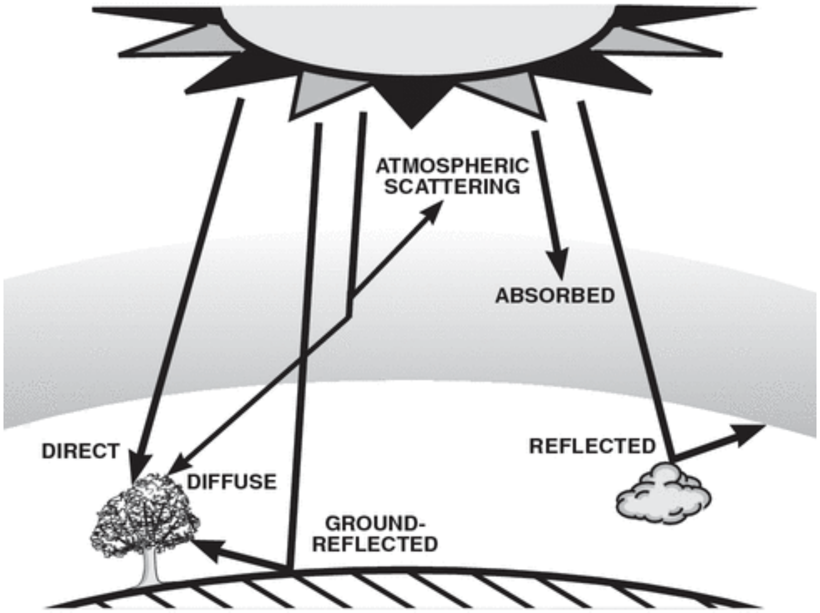

Figure 2.1 Three components of solar radiation (MNRE, 2000)

The terrestrial solar irradiation is a function of solar altitude, site altitude, albedo, atmospheric transparency and cloudiness. The atmospheric transparency is a function of aerosol concentration, water vapor as well as other factors. The presence of aerosols in the atmosphere attenuates the beam component, whereas it increases the diffuse component of the solar global irradiation. In essence, the beam component is converted to diffuse irradiation. Consequently, it may have a relatively small effect on the total solar global irradiation. Water vapor, on the other hand, attenuates both the beam and diffuse components, thereby, decreases the total solar global irradiation.

2.2 Historical perspective

A simple empirical linear relation was proposed by Angstrom (1924) i.e., the first correlation for estimating the monthly average daily global solar radiation on a horizontal surface $(\overline{H})$ (MJ/m^2 day) using sunshine duration. Prescott (1940) has put the Angstrom correlation in a more convenient form as,

$$\overline{H}/\overline{H}_0 = a + b(\overline{s}/\overline{s}_0) \qquad (1)$$

where *a* and *b* are constants, and $\overline{H}_0$ is the monthly average daily extraterrestrial radiation (MJ/m^2 day). $\overline{s}$ is the monthly average daily bright sunshine hours, and $\overline{s}_0$ is the maximum possible monthly average daily sunshine hours (day length). The regression constant *a* represents the case of overall atmospheric transmission for an overcast sky condition (i.e. $\overline{s}/\overline{s}_0 = 0$); while *b* is the rate of increase of $\overline{H}/\overline{H}_0$ with $\overline{s}/\overline{s}_0$ (Ogolo, 2010).

Since then, various investigators developed the empirical correlations using sunshine durations along with the different types of meteorological parameters such as latitude, ambient temperature, humidity, the elevation, water vapor pressure, etc. Garg and Garg (1983), Bahel et al. (1987), Gopinathan (1988), and Trabea et al. (2000) used the first order Angstrom type correlations with the varying data of different meteorological parameters. However, Singh et al. (1996), Fagbenle (1992), Shaltout (1985) and Ulgen and Hepbasly (2002) reported their different sets of constants for the second and the third order Angstrom type correlations. El-Sebaii and Trabea (2005) tested the first three order type correlations for Egypt and proved the suitability of the first order correlation.

In 1940, Prescott replaced the clear sky reference value by a rather more generalized 'Angot's value', i.e., the radiation on a horizontal surface with a transparent atmosphere (Akinuglo, 2008). He used the only available measured solar irradiation data in the continent to obtain the regression constants and utilized these to estimate the solar income for Acton, Canberra close to Mount Stromlo in Australia. Accordingly, Prescott drew on the published data of Angot's values rather than Angstrom's perfect clear sky value, which indicates "the solar radiation that would be received if the atmosphere were transparent (Akinuglo, 2008)." The formula was then named as Angstrom-Prescott correlation and the correlations and/or models which use the bright sunshine hours to estimate solar irradiation were named as sunshine-based models. Meanwhile, the regression coefficients were named as Angstrom coefficients.

It is rather easy to attribute rough physical meanings to coefficients a and b using the extreme values of n/N. If there is no cloud obscuring the sun within a day, then $n/N = 1$ and $H/H_0 = a + b$ can be interpreted as the monthly average daily value for the transmittance of a clear day. Note that clear day ($n/N = 1$ in this case) does not always mean a perfectly clear day without appearance of any cloud all the day. Even sometimes the presence of clouds that do not obscure the sun may increase the irradiation reaching the site due to high reflections. Another fact is that the days without any cloud may have different solar irradiation reaching the earth due to differences in the air mass and also due to some atmospheric conditions such as dense turbidity. For a completely overcast day, $n/N = 0$ and $H/H_0 = a$, which essentially accounts for the diffuse component.

An overall conclusion that can be derived from all these works might be summarized as: these coefficients depend on all physical, spatial and dynamic properties of the atmosphere at the region of interest. One may even state that for a region, the coefficients derived from a long term data of some number of years, can be different than those obtained by using the data of the same length for the same region but for another set of years. This is of course another research area of interest, which necessitates long-term reliable data with high accuracy from different regions.

Angstrom’s linear model relates global irradiation to sunshine duration by ignoring other meteorological factors such as the rainfall, relative humidity, maximum temperature, air quality, elevation above mean sea level, etc. The effects of other meteorological variables appear as deviations from the straight-line fit to the scatter diagram. In order to cover these errors to a certain extent, it is necessary to assume that the model coefficients are not constants, but random variables that change with meteorological conditions.

2.3 Review of Solar Radiation Research in India

The work of Pandey and Katiyar (2010) presents a statistical approach for the estimation of the diffuse/global irradiation on various inclined surfaces from the measured data of horizontal surface. The constants in the empirical equations to predict hourly solar radiation on a horizontal surface recommended by ASHRAE were modified by the authors (Parishwad et al., 1997) for Indian locations. In further studies, India was divided into four regions of rainfall, namely heavy, medium, low, and very low rainfall. Using ASHRAE equations with the modified constants, monthly-mean-hourly solar radiation values were estimated for ten cities from different regions of

India. From the comparative data analysis of the measured and estimated solar radiation of these cities, empirical correction factors for the four regions of rainfall were obtained (Parishwad, et al., 1997).

In India, the Meteorological Department measures sunshine duration, global radiation, and diffuse radiation at some selected places. The measured data of 21 years have been compiled and is available in the form of tables (Mani,1980) giving the monthly average values of hourly global and hourly diffuse values. Insolation and weather data for seventeen Indian cities were analyzed and correlated by Modi and Sukhatme (1979). Correlations, based on a city wise regression analysis, indicated that daily total insolation correlated best with sunshine duration, cloudiness and precipitation. However, these correlations were not useful for predicting insolation at locations where this data was not measured.

Hussain (1990, 1992) developed correlations for estimating monthly-mean daily beam, diffuse and global radiations from sunshine duration using Indian weather data for eight cities. He considered seasons in India such as pre-monsoon, monsoon, and post monsoon periods and climatic zones of India such as arid and semi-arid regions, and wet and dry regions, to obtain collective fits for each period. Singh et al. (1996) developed empirical relation to estimate global radiation from hours of sunshine. Reliable data on the duration of sunshine are available (Mani and Rangarajan, 1982) for 121 stations in India for periods ranging from 6-28 years. Correlations based on sunshine hours were not useful for places where such data was not available. Reddy (1971) proposed an empirical method for computing daily total solar radiation using sunshine hours, humidity and number of rainy days during the month. He tested his equation for only two locations, namely: Pune and Thiruvananthapuram. His equation gave large errors when tested for other locations (Modi and Sukhatme, 1979). Mani and Rangarajan (1982) have discussed an empirical method to compute solar radiation parameters under average overcast conditions. They suggested using mean ratio of daily-mean global radiation, measured on overcast sky condition, to that on clear sky conditions for 16 stations. The variation in this ratio among different stations represented variations caused by the characteristics of the cloud types found in different regions of the country. The authors have used a somewhat similar approach so as to estimate monthly mean- hourly solar radiation at any location in India using only longitude and latitude of the location, and its region of rainfall as input information.

Empirical equations can be found in the ASHRAE Handbook (1979) to estimate hourly-beam, diffuse and global radiation on clear days. The values of the constants in these equations were derived from the results of a study at the University of Minnesota (Threkeld et al., 1958). When these equations and constants were used to predict the solar radiation data for the Indian cities, the predicted values were found to be higher for normal beam radiation and lower for diffuse radiation. Hence, authors (Parishwad et al, 1997) found a new set of values of the constants to be used in these ASHRAE equations, suitable for India's great climatic diversity. It is observed that the estimated solar radiation data closely matches in the dry months, but differs with corresponding measured values due to cloudiness, which is related to rainfall.

Over five years (2001–2005), data of the global solar radiation on horizontal surface along with the bright sunshine hours of four prominent Indian cities viz. Jodhpur, Calcutta, Bombay, and Pune have been measured and analyzed (Pandey and Katiyar, 2010). The under considered cities have varying weather conditions. The regression constants have been calculated for the first, the second, and the third order Angstrom type correlations for each location using regression analysis method. Comparisons of monthly mean global solar radiation $(\overline{H})$ between the measured and the calculated values have been made.

In a study conducted by the Global Energy Balance Archive (GEBA), it was reported that regional trends in India include decreasing trends in measured and predicted solar radiation (Ramanathan et al., 2005; Gilgen and Ohmura, 1999). Analysis of trend always depends strongly on the time range of the data set. Mani et al. (1973) and Ganesan (1973) describe turbidity observations that begin in 1958 at Pune and New Delhi are supplemented in 1967–1969 at nine other sites in major cities.

Empirical correlations for estimating the ratios of monthly mean hourly to daily global solar radiation received on horizontal surfaces have been compared and their validity tested (Srivastava et al, 1995). The correlation of Collares-Pereira and Rabl (1979) yields the best results, while the correlations of Liu and Jordan (1960) and Garg and Garg (1983) give satisfactory values. Calculated ratios show small deviations from observed ratios around the solar noon. Measured ratios are generally lower than the calculated ratios in the morning and evening hours, while the reverse is observed for the hours around the solar noon.

Data from 27 meteorological stations is available in and near the Krishna basin. A total of 26 stations were maintained by the Indian Meteorological Department (IMD), and one was maintained by the International Crops Research Institute for the semiarid tropics (ICRISAT), in the city Patancheru. Four stations had SWSFC measurements for some years; Pune and Patancheru stations had the longest and most complete records. SWSFC at Patancheru was measured with a LI200X Silicon pyranometer calibrated to 400–1100 nm, with a mean accuracy of 3–5%. Mean monthly sunshine hours, defined as the number of hours of bright sunlight per day as measured by a sunshine recorder, were available for ten stations starting in the 1970s, but simultaneous cloudiness and sunshine data were available at only seven stations.

2.4 Modeling of Solar Power Plants

A very large number of PV system models are available, and the ones, which achieved the initial broad acceptance or dominant market share, are PCÔD and DESSIS (Klein et al., 1976). However, recently TRNSYS, developed by the Solar Energy Laboratory at the University of Wisconsin (Klein et al., 1976) and NREL's PV Watts, and commercial products such as PVSyst, are arguably the most important and influential models. TRNSYS is a general model designed to perform detailed simulations of time-dependent energy systems. As such, it has been used not just for photovoltaic system simulations, but other renewable energy systems, low-energy buildings, HVAC systems, and fuel cells. TRNSYS is expensive and general for some applications. So, while it has been used extensively for PV system, simulations by Sandia National Laboratories and a number of other researchers, many investigators have found or developed alternatives. One popular and well regarded alternative is PV-DesignPro (Pelosi, 2002), which differs from TRNSYS is that it emphasizes PV system design over detailed analysis. To this end, PVDesignPro relies heavily on well validated empirical models of PV panels and other system components. This approach makes PV-DesignPro excellent for understanding and evaluating the impact of design decisions on PV system energy production. However, it does not necessarily offer the physical insight that TRNSYS does. More recently, the U.S. Department of Energy (DOE) has released the SAM (SAM, 2007). Intended primarily as a policy analysis tool for DOE to use in making research funding decisions, SAM uses a subset of TRNSYS as its PV system modeling tool. Its design and physical analysis capabilities are limited.

While analytical models of PV system economics have existed for some time, more detailed numerical models are a relatively recent development. In the United States, SAM has rapidly become the most significant of these models. SAM calculates LCOE using a well established financial analysis procedure (Short et al., 1995), using installed PV system cost, ongoing operating and maintenance (O&M) costs, tax rates, financial incentives, and PV system performance estimates as its inputs. While SAM is arguably the most comprehensive economic analysis tool available for PV systems, its shortcomings in estimating energy production (resulting from its focus on policy analysis) limit its usefulness in analyzing the economics of real-world systems. Elsewhere, Natural Resources Canada has developed RETScreen (Natural Resources Canada, 2007), a set of renewable energy analysis tools with extensive financial analysis capabilities. However, as spreadsheet based tools, they are not capable of rigorous simulations to estimate energy production. Furthermore, like SAM, they are intended as policy analysis tools, thereby lacking many of the features desired for PV system design.

A similar tool with more emphasis on design and orientation is the On Grid Solar Financial Analysis Tool (Black, 2006) though it is targeted at professional PV system installers who wish to calculate economic return-on-investment (ROI) for their customers in California, where retail electricity rate schedules and the state's PV incentive program can be very complex. ROI is frequently of greater interest to end-users than LCOE, which has been used primarily for setting policy and industry targets, though LCOE is now gaining wider acceptance as a more general indicator of cost-effectiveness for renewable energy projects.

EL-Shimy (2009) investigated, from techno-economical and environmental points of view, the feasible sites in Egypt to build a 10 MW PV-grid connected power plant. Available PV-modules were assessed and a module was selected for their study. The long-term meteorological parameters for each of the 29 considered sites in Egypt from NASA renewable energy resource website (Surface Meteorology and Solar Energy) were collected and analyzed in order to study the behaviors of solar radiations, sunshine duration, air temperature, and humidity over Egypt, and also to determine the compatibility of the meteorological parameters in Egypt with the safety operating conditions (SOC) of PV-modules.

Dalton et al. (2009) outlines a feasibility analysis of renewable energy supply (RES) for small to medium-scale tourist operations (less than 100 beds) dependent on stand-alone supplies. The analysis utilized the power load data from three accommodation case studies that had RES/hybrids already installed. The accommodation sites, chosen from diverse locations within Australia, varied in both climatic and geographic characteristics. The assessment criteria for the analysis were net present cost (NPC), renewable factor (RF) and payback time. Payback time analysis for stand-alone RES has been conducted in only two previous studies. A Greek study quoted a payback time of 5.7 years for a large-scale Wind Energy Conversion Systems (WECS) installation on a remote island (Kaldellis etal., 2010, and an Australian study quoted a payback time of 4.3 years for a large-scale WECS installation in a large hotel (Dalton et al., 2008). All remaining studies examine grid-connected RES and quote payback times ranging from five to eight years for PV systems (Fernandez-Infantes et al., 2006).

One of the other major challenges for the PV energy system remains matching the intermittent energy supply with the dynamic power demand. This problem can be solved by exchanging power with the electrical grid. However, for the stand-alone PV system (Chiang et al., 1998), certain energy storage devices must be added into the system so as to provide power-on-demand. These devices must store PV energy in excess of electricity demand and subsequently meet electricity demand in excess of PV energy. Three stand-alone photovoltaic power systems using different energy storage technologies were studied by Li et al. (2009). Key components including PV modules, fuel cells, electrolyzers, compressors, hydrogen tanks and batteries are modeled in a clear way so as to facilitate the evaluation of the power systems. Based on energy storage technology, a method of ascertaining minimal system configuration is designed to perform the sizing optimization and reveal the correlations between the system cost and the system efficiency. The three hybrid power systems, i.e., photovoltaic/battery (PV/Battery) system, photovoltaic/fuel cell (PV/FC) system, and photovoltaic/fuel cell/battery (PV/FC/Battery) system, are optimized, analyzed and compared. The obtained results indicate that maximizing the system efficiency while minimizing system cost is a multi-objective optimization problem. As a trade-off solution to the problem, the proposed PV/FC/Battery hybrid system is found to be the configuration with lower cost, higher efficiency and less PV modules as compared with either single storage system (Li et al., 2009). Vosen and Keller (1994) analyzed the cost and efficiency of PV power systems with different combinations of energy storage devices. A hybrid energy storage system coupled to PV generation was evaluated by Maclay et al. (2006).

Chapter - 3

Assessment and Uncertainties of Solar Resource Data in India

3.1 Introduction

Detailed solar and weather condition assessments are necessary to understand project economics for solar power systems. In Solar PV plants for example, the plant's operating capacity is highly sensitive to global GHI and the consequent bearing on the project cost is significant. For a given MW capacity, the GHI will determine the plant size (number of panels required, land requirement etc.), capacity factor and plant costs. A change in GHI directly impacts the electricity production and in turn, the revenues realized. It is to be noted that understanding the project costs and returns after accounting for the impact of solar radiation levels will have an impact on tariff expectations. Similarly, a detailed understanding of DNI is critical for solar thermal systems and consequently it is a critical component of the technical analysis for the development of the solar plant.

Ideally, local radiation measurements should be undertaken over several years to obtain a sense of the long-term DNI resource. However, since most companies are eager to complete financing within a year or so, it is also necessary to find methods of proper time-extrapolation.Another approach is to use site-specific modelled data, which is collected by obtaining measured data from a nearby station and estimating what the resource might be at other interesting sites in the area. Two further types of modelled data include publicly available and commercial gridded-data. This is gathered using satellite algorithms to infer atmospheric conditions and calculate the down-welling solar irradiation at ground level from radiative transfer modelling. Although satellite-derived DNI products could, in principle, be more accurate than measurements, current accuracy remains poor, mainly due to difficulties in retrieval of atmospheric condition data since all models rely on (often inaccurate) aerosol information. Because models use different sources for clouds and aerosols it is normal to find significant differences in predictions - the exact cause of which, remains elusive.

Extensive and reliable solar resource data will significantly boost the development of Indian solar energy sector. Being a relatively new technology, high-quality solar resource information is indispensible for selecting suitable project sites, design and optimization of the project and reasonably predicting the long term availability of solar energy that determines the financial viability of a solar project. The usage of solar data of high or unknown certainty results in an increased risk in the financial plan; discourages lenders from participating in projects; lenders seek high interest charges or onerous securities, and very often a failure to meet the financial closure deadlines. Banks in general are risk averse, particularly when considering projects that use technologies without an established track record.

In India, solar resource data is drawn from various sources. These include recently installed state-of-the-art 51 solar meteorological stations throughout the country, Solar Radiation Handbook particularly Solar Radiant Energy over India prepared jointly by IMD and MNRE, the Indian Meteorological Department, National Aeronautics and Space Administration (NASA's) Surface Meteorology and Solar Energy data set, METEONORM's global climatological database, and satellite derived geospatial solar data products from the United States National Renewable Energy Laboratory (NREL), MNRE and IMD joint venture and several satellite based data service providers.

3.2 Current Status of Solar Radiation Data in India

One of the major challenges in the development of solar power in India is the absence of ground solar radiation data. Direct normal irradiation (DNI) plays a key role in the design of concentrating solar power (CSP) plants. There are several data sources for weather and solar radiations in India. One of the literary sources (Mani, 1980, 1982) provides measured values of global and diffuse solar radiations for various locations in India for one representative a day of each month for a 10-20-year period. Surface meteorology and Solar Energy (SSE) data sets are formulated from NASA satellite and insolation, and meteorological data for the 22-year period (July 1983- June 2005). Results are available for 1° latitude by 1° longitude grid cells over the globe (NASA, 2010). The Indian Society of Heating, Refrigerating and Air-Conditioning Engineers (ISHRAE) developed the building energy performance simulation programs, an outdoor design conditioned in typical meteorological year (TMY2) format for 58 Indian cities (ISHARE, 2011).

Solar energy potential in India can be estimated using Meteronorm2 data and TRNSYS software. TRNSYS consists of weather files (TMY files) for several Indian locations, which contains hourly values of global, diffuse and direct solar radiations. Meanwhile, NREL hourly data

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[2] METEONORM is a comprehensive meteorological reference, incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location in the world. It is based on over 20 years of experience in the development of meteorological databases for energy applications. METEONORM addresses engineers, architects, teachers, planners, and anyone interested in solar energy and climatology. The database includes climatological data of 7700 weather stations (60 stations of India) based on measured climatic parameters viz. solar radiation, temperature, humidity, precipitation, days with precipitation, wind speed and direction, sunshine duration, etc. including complete coverage of the global, including polar regions.

and maps cover India at 10-km grid (0.1x0.1) spatial resolution (NREL, 2011). The monthly and annual direct normal irradiance (DNI) and global horizontal irradiance (GHI) maps were developed from hourly data spanning from January 2002 to December 2008, generated through an application of the SUNY satellite to irradiance model (Perez, 2002, 2004). Monthly gridded AOD values were developed for each month of the SUNY model run for India. This approach was adopted based on evidence of changing AOD over time in India (Datar, 1996; Porch et al, 2007; Ramanathan et al, 2005). As per IMD estimates, the annual global radiation in India varies from 1600 to 2200 kWh/m^2, which is comparable with radiation received in the tropical and sub-tropical regions. The equivalent energy potential is about 6,000 million GWh of energy per year. Although the highest annual global radiation is received in Rajasthan, northern Gujarat, and parts of Ladakh region, the parts of Andhra Pradesh, Maharashtra, Madhya Pradesh also receive fairly large amount of radiation as compared to many parts of the world especially Japan, Europe and the US, where development and deployment of solar technologies is maximum. Horizontal global radiation data have been recorded at many meteorological stations in India, but the corresponding diffuse radiation records are scarce at some stations. Diffuse radiation must be estimated through models and correlations. The study of correlation between global and diffuse solar radiation is limited in India. Also, existing solar radiation models contain empirical constants, which depend on the season and the geographical location of the place.

The following is a brief description of these sources. Except data from MNRE-CWET all the other sources are based on the synthetic generation of data based on various models (interpolation, reanalysis, NWP, satellite estimations etc.)

National Renewable Energy laboratory, US & Ministry of New and Renewable Energy, India: The NREL-MNRE-IMD data is available as solar resource maps, which have a resolution of 10 kms. These maps have been developed using weather satellite data incorporated into a site-time specific solar mapping approach developed at the U.S. State University of New York at Albany (SUNY model). The model was developed for US based GOES satellite images and adapted for Meteosat satellite images.

Ministry of New and Renewable Energy and CWET: MNRE-CWET has carried out 51 ground mounted solar radiation stations in India. The available radiation data set includes DNI, GHI & DHIdata for more than one year. Data collected so far does not provide accurate and precise input for power plant output calculations.

MNRE-IMD: Solar Radiant Enery over India, solar radiation handbook

3TIER: 3TIER is a global solar resource assessment firm and largely uses the SUNY model for its estimation from Meteosat generation satellite images with temporal and spatial resolution of 30 minutes and 5 KM respectively. The dataset over India is based on over 10 years of half-hourly high-resolution (roughly 2.5 km) visible satellite imagery from Meteosat satellite data (i.e., the geostationary Meteosat 5 and Meteosat 7 satellites operated by EUMETSAT), using the broadband visible wavelength channel.

Irsolav-CIEMAT: Spanish affiliate of CIEMAT has developed its satellite modeling based improved Heliosat-3aalgorithm with 5 KM spatial and hourly or half hourly temporal resolution, based on Meteosat First Generation satellite images from 1999 to the current period with extensive computations of Linke Turbidity factor (comprising of daily AOD from MODIS, MISR and MACC satellites and water vapor from NCEP) based on daily averages.

Geomodel: Solar GIS estimates solar radition data from Meteosat generation satellite with hourly temporal and 5 KM spatial resolutions. The irradiance components are the results of a five steps process: a multi-spectral analysis which classifies the pixels, the lower boundary (LB) evaluation is done for each time slot, a spatial variability is introduced for the upper boundary (UP) and the cloud index definition, the Solis clears sky model is used as normalization, and a terrain disaggregation is finally applied.

In order to study the behavior of global solar radiation and sunshine duration over India, the long-term (10 years) values were obtained using the long-term site averages. Figure 4.1 shows map of India, released by Ministry of New and Renewable Energy (MNRE), with solar radiation levels in different parts of the country.

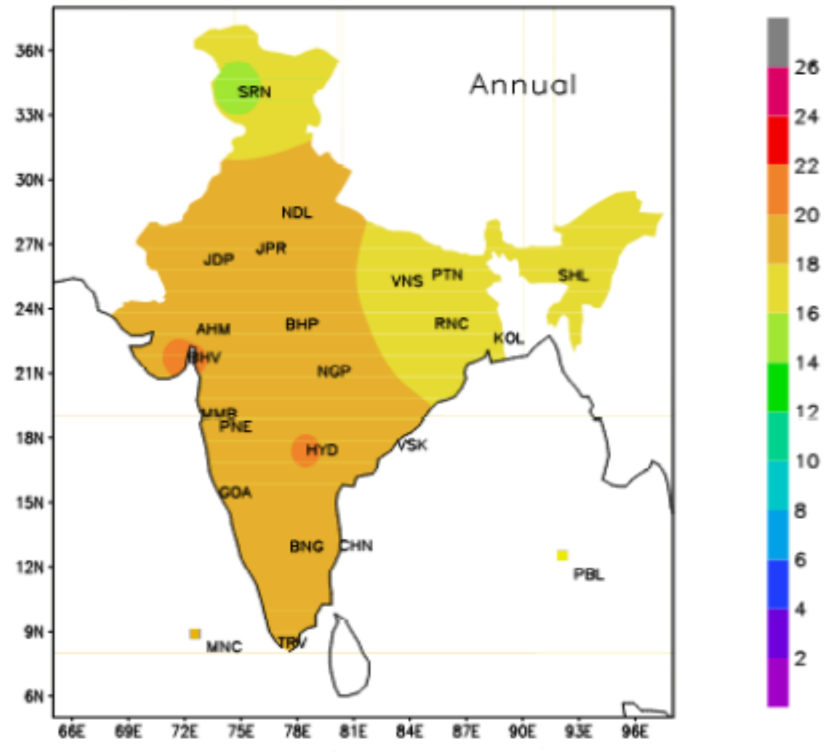

Figure 3.1 Global solar radiation exposure over the year based on IMD site data–MJ/m^2 (MNRE,2010)

3.3 Uncertainties In Available Datasets

The solar radiation data available from different sources possess many variations as described below:

Validation of Satellite and Ground Data: No attempt has been made so far to correct (and remove modeling bias for greater accuracy and characterization)satellite estimated data with accurate ground data. Attempt to validate the ground data have brought unexpectedresults with DNI being very low. Therefore there is an urgent need to first validate ground measured data using the latest filters (physical, cross component, stringent cross component) based on methodology developed by BSRNand then to “correct” the missing and erroneous data with high resolution satellite estimated data. Most existing satellite models have been built without either validations from ground measured data, questionable aerosol data of unknown quality or accuracyor using synthetic U.S. and/or European data and need extensive validation for India, taking into account site specific atmospheric conditions e.g. Aerosol Optical Depth (AOD[3]).

Distance: Research paper have shown that ground data extrapolated beyond 5 KM have lower accuracy than from typical measurement stations.The current MNRE-CWET and IMD stations are far away from the identified sites. Satellite based estimations are increasingly being favored for solar resource estimation for sites that are more than 5 KM away from ground stations. However, it must be pointed out that ground stations form the basis for establishing "ground truth" and the estimations are almost always considered with statistical deviations between ground truth and satellite estimations, including long term forecast and Pxx estimations required for bankability.

Granularity: The NREL-MNRE model is based on a 10km grid which is not considered very granular. Satellite images are available over Indian Ocean Region with 3 – 5 KM spatial and half-hour temporal resolutions.Granularity can therefore be improvedto 5 KM and accuracy of satellite estimated data improved byvalidated and corrected with ground measured data frommultiple locations. As an example, Texas alone has over 90 ground measurement stations.

Frequency of Measurement and Estimation: Satellite images with half-hourly temporal resolution are available. Current satellite based data models are based on monthly averages of aerosols and water vaporwhile the recommended input is computation of Linke Turbidity function from multiple sources (MODIS, Aeronet, MISR, MACC) including from correction algorithms based on ground measured solar data to improve theaccuracy and characterization of the solar resoure.

Correlation of Data Sources: There is large variation in data from different sources e.g. the two estimations from the SUNY model using different estimations of AOD (single value vs monthly values) show different outputs and for DNI dataset in Jodhpur shows up to a 35% higher estimation than ground measured data provided by IMD. It is proposed that after establishing the quality, accuracy and relaibilty of ground measured data, statistical deviations (rRMS and rBIAS) be determined and form the basis for accuracy of satellite estimated data used for "bankability"

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[3] *AOD is a measure of the attenuation of solar radiation resulting from the scattering and absorption of light within an atmospheric column. It has high impact on the DNI estimations and one of the main reasons for difference between the satellite and ground mounted met-station data.*

These variations therefore result in the following issues:

- While potential is generally known, it has not been accurately quantified
- Confidence in models is not very high, given the high variation between datasets from different sources and limited reliability of ground data
- Ground measurements, wherever they exist, have neither been considered complete, accurate nor reliable
- Without confidence and validation, data cannot be considered bankable

The significant impact that measurements of solar radiation and climatic conditions will have on a solar power projects has led investors and project developers to stress the importance of gathering detailed information for potential sites. Ideally, on the ground measurement should be collected over a period of 10 – 30 years. In addition, ground measurements should be compared and correlated to onsite and nearby site satellite-based analyses to present a comprehensive understanding to project stakeholders.

3.4 Gaps in the Study

Solar PV and CSP need detailed modeling and technology identification along with a proper solar radiation resource assessment. Research about the direct and diffuse components of the solar radiation is less prolific, mainly because of the scarce availability of such data. Moreover, most of the direct component analyses involve the use of data obtained from the differences between measured global and diffuse radiations.

Nevertheless, one shared pitfall for most analyses of solar radiation variability is that they were carried out using local data bases. This implies that the proposed models are site dependent and new evaluations must be performed when using data sets from other locations. Finally, the analysis devoted to the behavior of the direct and diffuse components are still scarce. In the last years, these components are being investigated for some special spectral regions from the statistics point of view. Present work first lay out arguments for choosing an existing solar resource data set for India based on a number of sources, then applying that data to models that simulate PV and CSP plant configurations at specific locations.

Chapter – 4

Application of Existing Data to Assess the Viability of PV Applications

4.1 Introduction

The global economic and political conditions that tend to make countries more dependent on their own energy resources have caused a growing interest in the development and use of renewable energy (National Renewable Energy Laboratory, 1996). According to Fanchi (2004), energy consumption in developed and developing countries grow at an annual rate of approximately 1% and 5%, respectively. There has been a growing interest in the development and use of renewable energy sources as countries seek to be more energy-independent in today's global economic and political conditions (NREL, 2006). Solar energy has emerged as one of the leading renewable options for meeting demands especially in developing countries like India and China. In terms of its environmental advantages, solar energy generates electricity with insignificant contribution of CO_2 or other GHG to the atmosphere and they produces no pollutant discharge on water bodies or land mass (EL-Shimy, 2009).

There is an immense potential to tap solar energy in India. Charan (2009) believed that the country's ability to secure a reliable supply of energy resources at affordable prices will be one of the most important factors in shaping its future energy demand. Given the potential, solar contribution in India has been less than 5% of the total generation capacity from renewable energy sources, falling far behind wind energy, small hydro and biomass. Most of the solar power plants are concentrated in USA, Spain and Germany.

There are many technical and financial issues concerning the viability of a solar PV power plant including accurate and reliable global and diffuse solar radiation data measurement, high capital cost of the project, financial incentives from the government and selection of sites in India for setting up solar PV power plant. Researchers elsewhere (Hrayshat, 2009; Ekren and Ekren, 2009; Bazen and Brown, 2009) have identified certain parameters to know viability of solar PV as an electricity generation source. Most of the work is confined to identification of parameters like electricity generation, simple payback period, internal rate of return (IRR), GHG emissions etc. Parameters like these have been identified because these factors cover viability of PV against the existing fossil fuel based electricity generation. All remaining studies examine grid-connected renewable energy system (RES) and quote payback times ranging from five to eight years for PV systems (Fernandez-Infantes et al., 2006). The parameters identified by authors for countries like Jordan, Egypt etc should apply to Indian scenario as well. India's renewable energy was launched primarily as a response to the professed rural energy crisis in the 1970s, the renewable energy program gained momentum with the economic liberalization program which began in the early 1990s (Venkata et al., 2001), with the emphasis shifting from purely subsidy-driven dissemination program to technology promotion through the commercial route. It is attempted to provide an integrated solution to the above mentioned issues by investigating techno-economical and environmental points of view, the feasible sites in India to build a 5 MW PV-grid connected power plant.

4.1.1 Solar Radiation over India (Source NASA)

In this chapter, solar radiation data are based on NASA's renewable energy resource website (Surface Meteorology and Solar Energy) (NASA, 2010) is an input to RETScreen model.

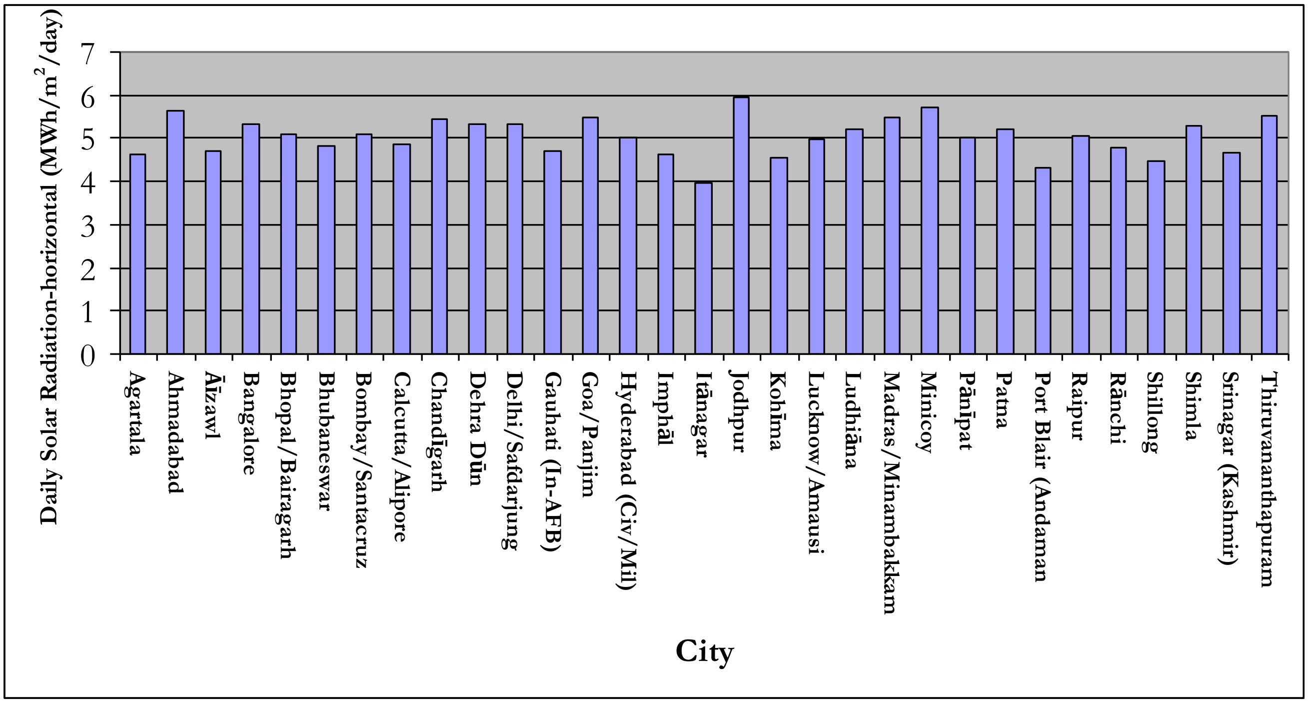

Figure 4.1 Annually averaged solar radiation exposure for the year 2010 over selected site of India based on NASA satellite data

The global solar radiation is geographically dependent such that it varies from a minimum value of 3.95 kWh/m^2/day at Itanagar (East India) to a maximum value of 5.94 kWh/m^2/day at Jodhpur (Desert area in West India) (Figure 4.1). It can be observed that the highest annual global radiation is received in Jodhpur, Rajasthan at 5.94 kWh/m^2/day, northern Gujarat at 5.7 kWh/m^2/day and parts of Ladakh region, the parts of Andhra Pradesh at 4.9 kWh/m^2/day. Other states like Maharashtra (Mumbai/Santacruz 5.1 kWh/m^2/day), and Madhya Pradesh (Bhopal 5.1 kWh/m^2/day) also receive fairly large amount of radiation as compared to many parts of the world especially in Japan, Europe and the US, where the development and deployment of solar technologies is maximum. Thus, although solar radiation is good in many parts of India, there is, however, no rigorous study that has been done to estimate the impact of solar radiation on viability of Solar PV at different sites.

4.1.2 Air Temperature and Relative Humidity

A study on the long-term monthly average relative humidity and the long-term monthly average air temperature is carried out with relevant data obtained from NASA (NASA, 2010). The temperature and humidity related to Standard Operating Conditions (SOC) requirements for the PV-module are between 20^{o}C and 40^{o}C for SOC temperature and from 45% to 90% for SOC humidity. The long-term monthly average relative humidity (%) and the long-term monthly average air temperature (^{o}C) at 10 m above the surface of the earth are shown in Figures 4.2 and 4.3, respectively. Based on Figures 3.3 and 3.4, both the long-term temperature and humidity for different sites in India agrees with the SOC of the PV-module. From Figure 3.3, it can be seen that the average air temperature over India decreases from south to north with an average air temperature of 21.8 ^{o}C over the entire region, which is within the SOC of the considered PV-module.

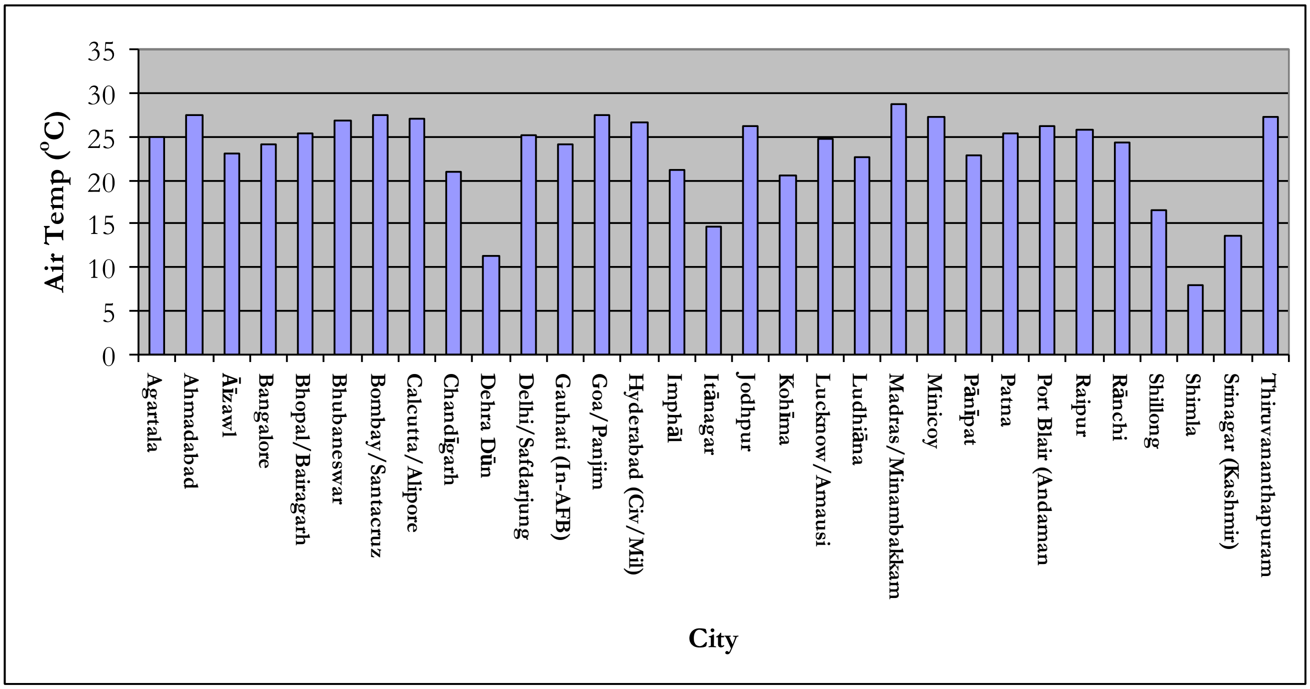

Figure 4.2 Variation of air temperature over selected sites in India (averaged annually)

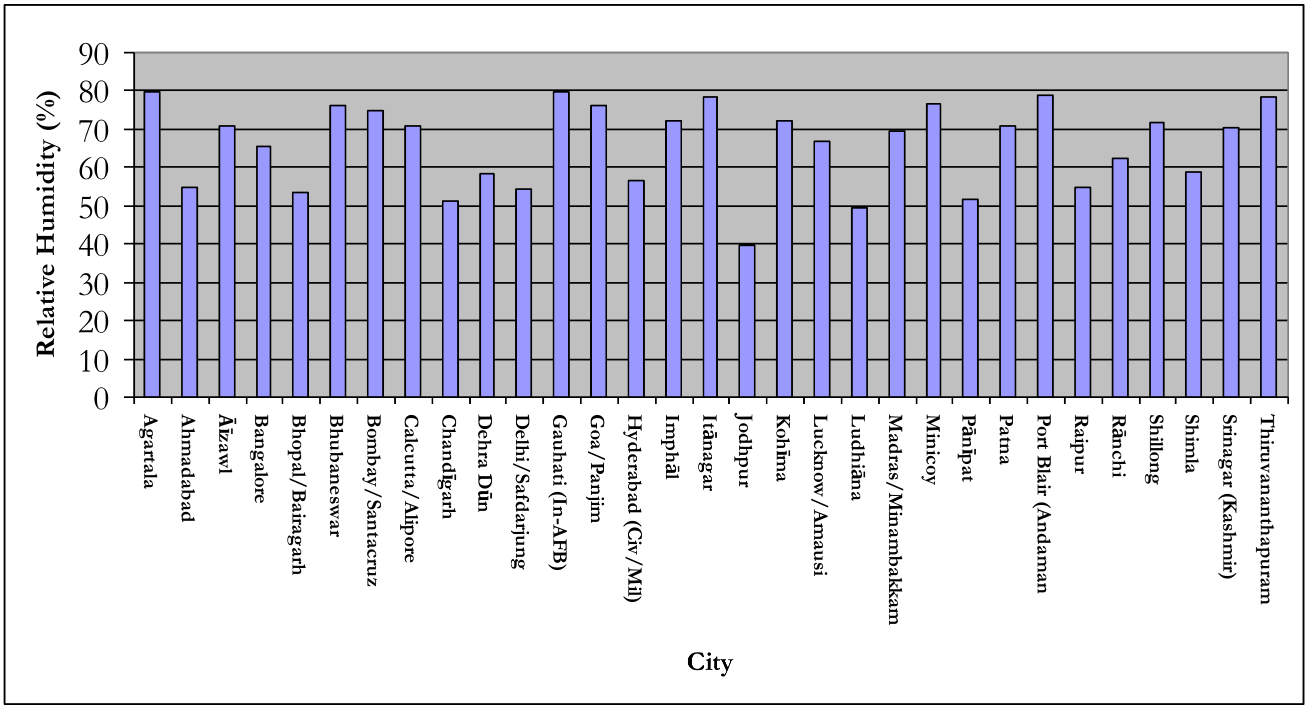

Figure 4.3 Variation of relative humidity over selected sites in India (averaged annually)

4.1.3 Financial Incentives by the State and National Governments

The Jawaharlal Nehru National Solar Mission (JNNSM) (23rd November 2009), is an initiative by the Government of India that seeks to support the growth of solar energy in the country. A key lever that has been designed to drive the participation of solar generating companies is a feed-in tariff which has been coupled with a unique power sale structure (CERC, 2010). Table 3.1 summarizes the assumptions and incentives announced by Centre Electricity Regulatory Commission (CERC) for setting up solar PV power plants in India.

Table 4.1 Financial Assumptions for Solar PV Power Plant

Assumption Categories	Photovoltaic
Capital Cost (INR in Crores / MW)	16.9
Capacity Utilization Factor (%)	19
Debt to Equity Ratio (%)	70:30
Loan Term (Years)	10
Interest Rate (%)	13.5
Depreciation (%)	7% for 10yrs
Duration of Tariff (Years)	25
Tariff Rate (INR / kWh)	17.91

4.2 RETScreen Model and Methodology

RETScreen is the most comprehensive software product of its kind, allowing engineers, architects and financial planners to model and analyze any clean energy project. Decision-makers can conduct a five step standard analysis, including energy analysis, cost analysis, emission analysis, financial analysis and sensitivity/risk analysis. Fully integrated into these analytical tools are product, project, hydrology and climate databases (the latter with 4,700 ground-station locations plus NASA satellite data covering the entire surface of the planet), as well as links to worldwide energy resource maps (RETScreen, 2010). Figure 3.5 refers to the scheme for evaluating techno-commercial viability of 5 MW solar PV power plants in India, used in the present study.

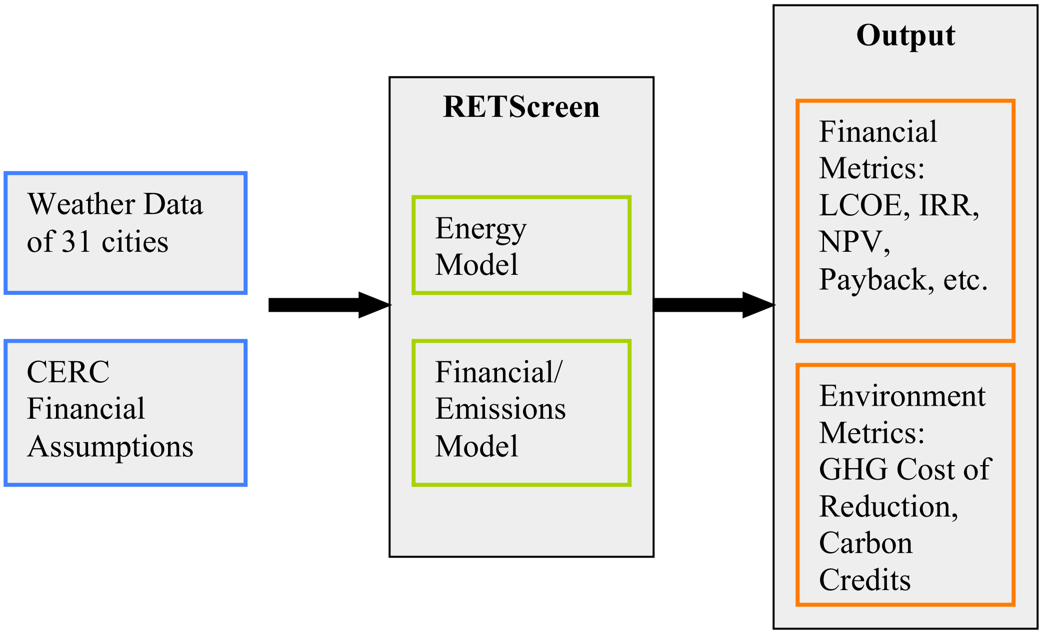

Figure 4.4 Scheme for evaluating techno-commercial viability of Solar PV power plants in India

4.3 Results and Discussion

The financial evaluation used discounted cash flow (DCF) to calculate a levelized cost of generation and a net present value (NPV) analysis to assist in the selection of the preferred solar generation technology. A financial evaluation of the 5 MW solar PV project, assuming a 25-year project life for 31 cities is undertaken and the key results are:

4.3.1 Pre-tax cash flows and internal rate of return (IRR)

The calculation of cash flows keeps track, on a yearly basis, of all expenses (outflows) and incomes (inflows) generated by a clean energy project. The IRR is the discount rate that causes the NPV of the project to be zero. The economic indicator pre-tax IRR equity (Figure 3.6), which varied between a minimum of 9.9% for Itanagar, Shillong and a maximum of 19.9% for Jodhpur, Rajasthan with an overall mean value of 15.2% for 31 sites across India. East and north-eastern states show significantly lower pre-tax IRR equity values compared to northern, southern and western regions of India.

The economic indicator after-tax IRR equity (Figure 4.5), which varied between a minimum of 7.8% for Itanagar, Shillong and a maximum of 18.3% for Jodhpur, Rajasthan, closely followed by Shimla at 17% with an overall mean value of 13.3% for 31 sites across India.

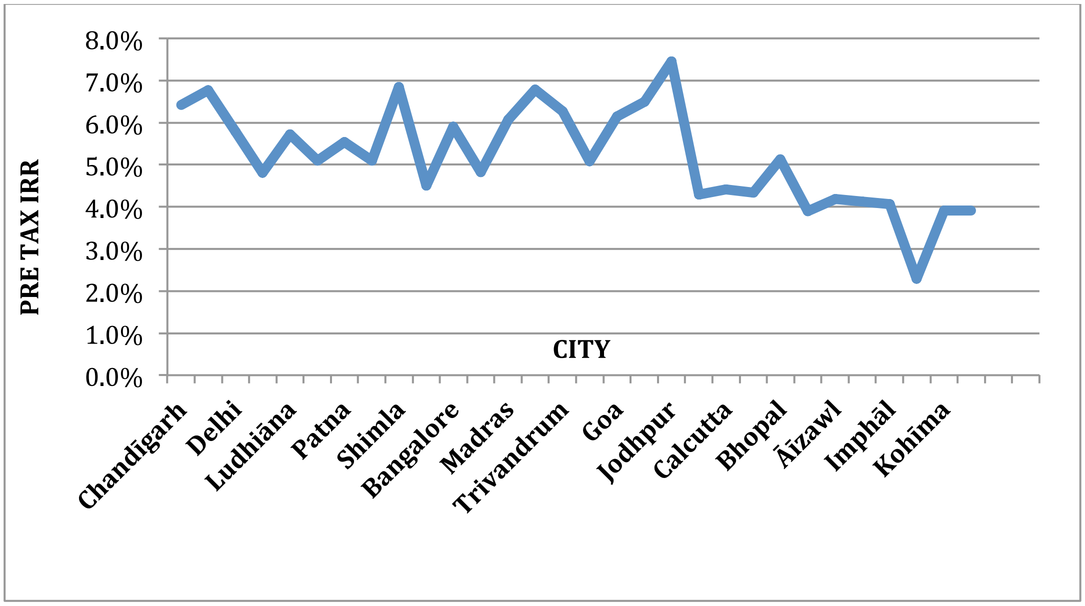

Figure 4.5 Pre-tax IRR-Equity for different cities of India as per the RETScreen Model

4.3.2 Simple payback period (SPP)

SPP is the number of years that takes for the cash flow (excluding debt payments) to equal the total investment (which is equal to the sum of the debt and equity).

As seen in Figure 4.7, the economic indicator SPP varied between a minimum of 7.5 years for Jodhpur and a maximum of 10.7 years for Itanagar with an overall mean value of 8.8 years for 31 sites. Lowest SPP value for Itanagar indicates that the project would be least economically viable if implemented here. Peak SPP value is for Itanagar in north eastern India. Eastern and north eastern locations have a higher value of simple payback period. Shimla in north, Minicoy in south, Bhopal in east have least SPP values in their respective regions.

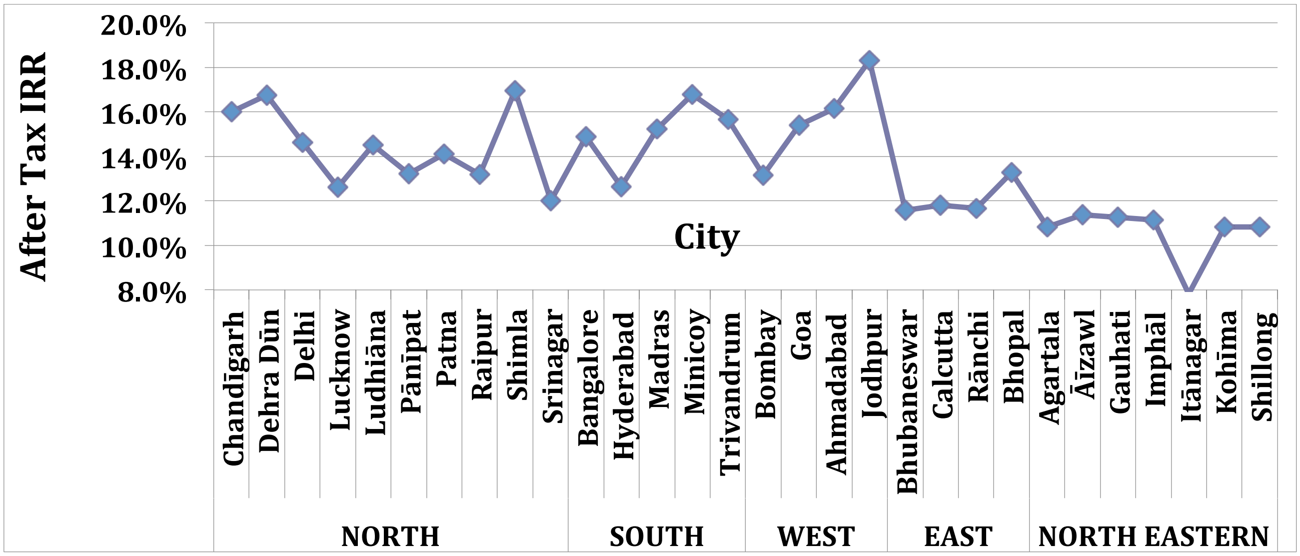

Figure 4.6 After-tax IRR-Equity for different cities of India

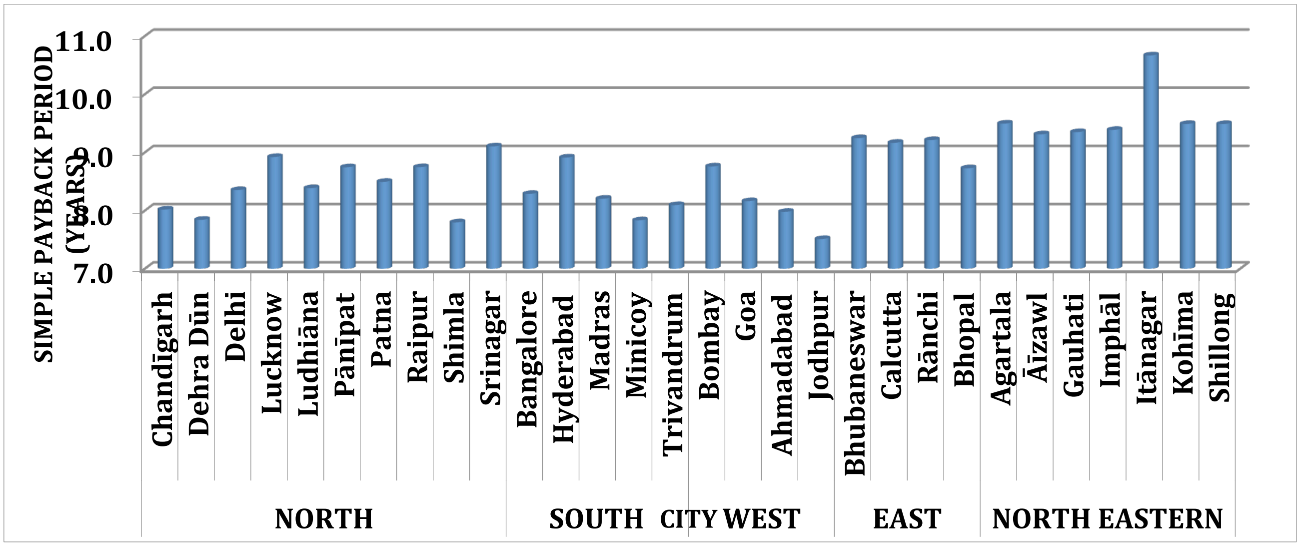

Figure 4.7 Simple Payback period (SPP) for different cities of India as per the RETScreen Model

4.3.3 Net present value (NPV)

NPV of a project is the value of all future cash flows, discounted at the discount rate, in today's currency. The economic indicator NPV (Figure 4.8) varies between a minimum of 86 million Indian Rupees for Itanagar and a maximum of 285 million and 239 million Rupees for Jodhpur and Shimla, respectively. Higher NPV for Western regions like Goa, Ahmedabad and Jodhpur, Southern regions like Mincoy, places in northern India like Shimla, Dehradun and

Chandigarh equate to better investment opportunities. Solar projects in Itanagar cannot be considered due to negative NPV which would mean negative cash flows. East and North Eastern regions depict very low NPV values which indicate that solar project development in these areas are not financially viable.

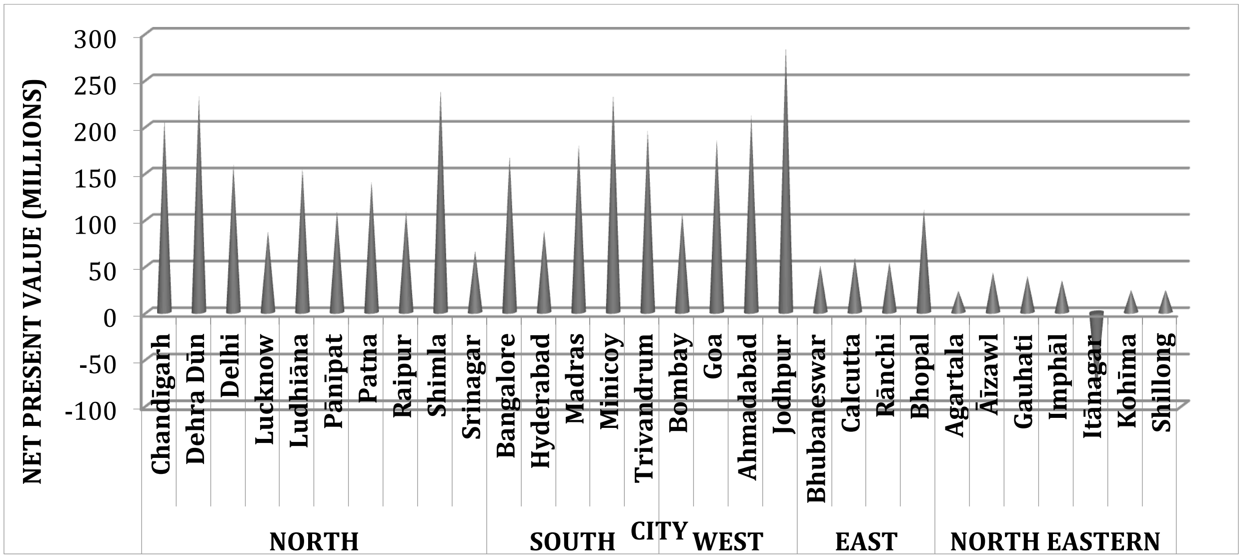

Figure 4.8 Net Present Value in Indian rupees for different cities of India as per RETScreen Model

4.3.4 Annual life cycle savings (ALCS)

ALCS is the levelized nominal yearly savings having exactly the same life and net present value as the project. The economic indicator ALCS (Figure 4.9) varies between a minimum of 10 million Indian Rupees for Itanagar, and a maximum of 33, 28, and 25 million Rupees for Jodhpur, Shimla, and Ahemdabad, respectively. Jodhpur in the west has the highest ALCS value, whereas Itanagar in north-east has the lowest value. Dehradun, Shimla and Chandigarh in the north; Minicoy and Trivandrum in the south have high ALCS values. ALCS values for Eastern and north-eastern locations do not exceed 13 million rupees.

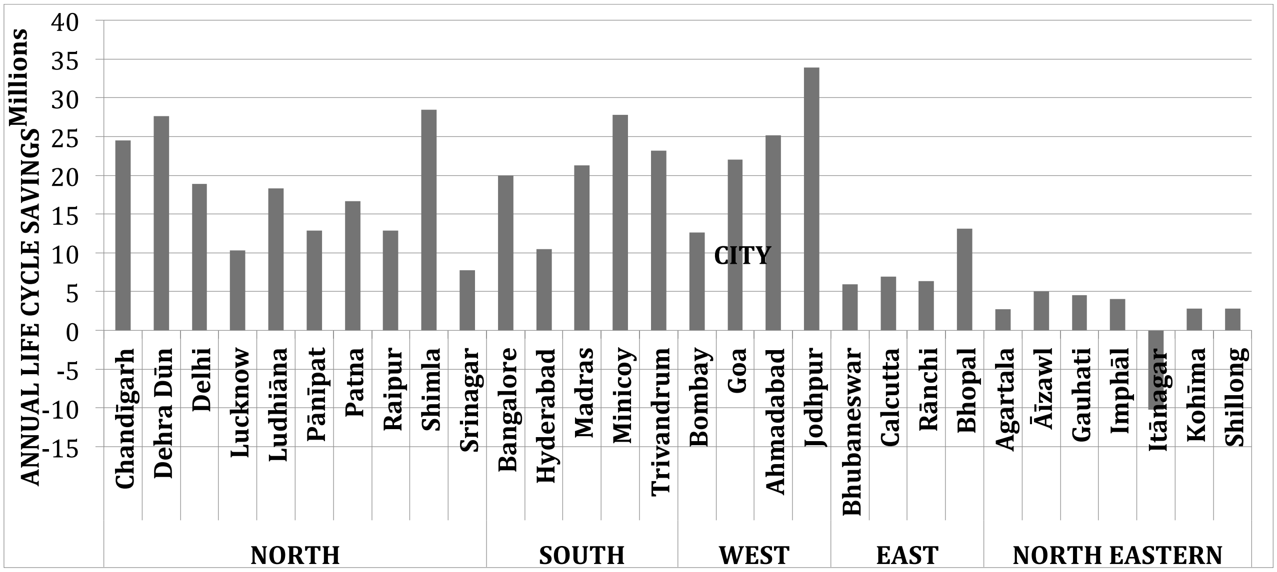

Figure 4.9 Annual Life Cycle Savings in INR for different cities of India

4.3.5 Benefit-Cost (B-C) ratio

B-C ratio is an expression of the relative profitability of the project. It is calculated as a ratio of the present value of annual revenues (income and/or savings) less annual costs to the project equity as shown in Figure 4.10.

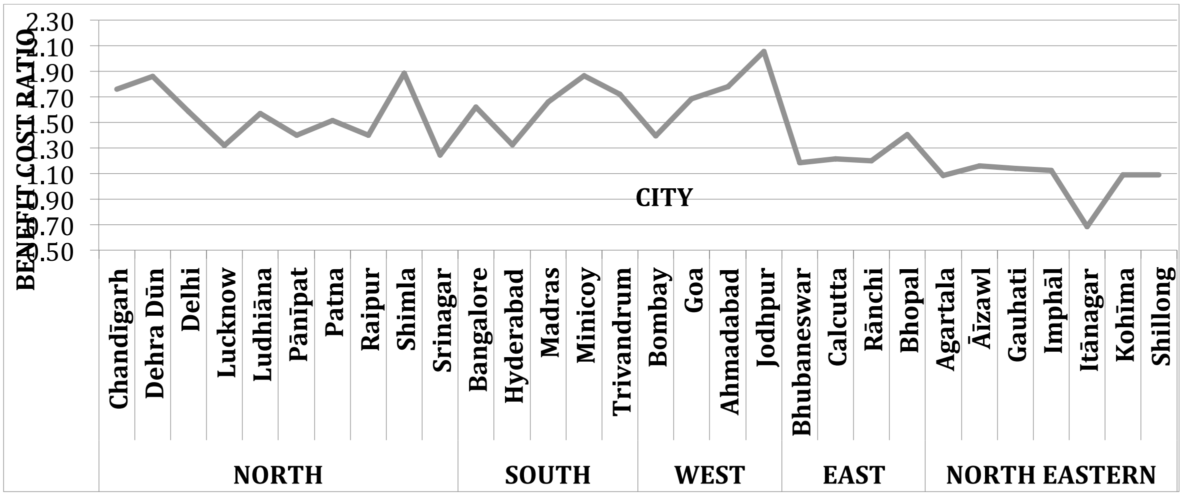

Figure 4.10 Benefit-Cost ratio for different cities of India as per RETScreen Model

The economic indicator B-C ratio varies between a minimum of 0.68 for Itanagar and a maximum of 2.05 for Jodhpur, followed by 1.86 for Minicoy and Dehradun with an overall mean value of about 1.41 for 31 sites across India. All the locations in eastern and north-eastern region of India show a very low benefit-cost ratio, with Itanagar depicting lowest ratio of 0.68. Mincoy (ratio 1.86) in the south; and Shimla (1.88) and Dehradun (1.86) in the northern part of India show a high B-C ratio.

4.3.6 Energy production cost

The energy production cost is the avoided cost of energy that brings the net present value to zero. This parameter is not included in the combined heat and power model, since there are potentially many types of energy produced, each having a distinct production cost .

The economic indicator cost of energy (COE) (Figure 4.11) varies between a minimum of 10,448 INR/kWh for Jodhpur and a maximum of 14,791 INR/ kWh for Itanagar, with an overall mean value of 12,195 INR/kWh for India (31 sites). Shimla in the north, Minicoy in the south, and Bhopal in the east have the lowest COE values. All east and north eastern regions have very low COE values.

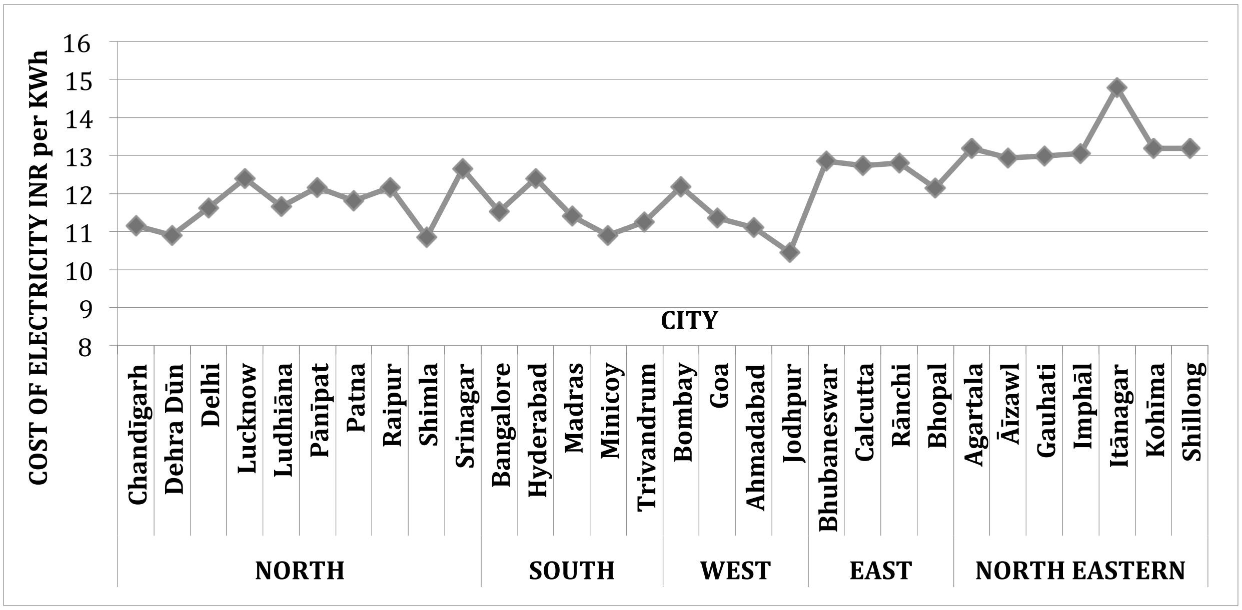

Figure 4.11 Cost of Electricity in INR per MWh for different cities of India as per RETScreen Model

4.3.7 GHG emission reduction cost

The GHG emission reduction cost (*GRC)* represents the levelized nominal cost to be incurred for each tonne of GHG avoided. The RETScreen GHG Emission Reduction Analysis Model helps to estimate the GHG emission reduction (mitigation) potential of a proposed clean energy project. The GHG analysis model is common to all RETScreen clean energy technology models. It calculates the GHG emission profile for a base case system (baseline) and for the proposed case system (clean energy project). The GHG emission reduction potential is obtained by combining the difference of the GHG emission factors with other information calculated by RETScreen, such as the annual energy delivered.

The avoided GHG emissions led to GHG reduction costs (Figure 4.12), which varied between a minimum of 1345 tons/year for Itanagar and a maximum of 3,178 and 2,763 tons/year for Jodhpur and Shimla, respectively, with an overall mean value of 1,359 tons/year of GHG reduction cost in India across 31 sites. East and north eastern locations show a higher GHG reduction cost. GHG reduction cost values for northern India range from as low as -2763 for Shimla to -879 for Srinagar. In the south, Minicoy (-2712) and Hyderabad (-1154) present the lowest and highest GHG reduction cost respectively. Bombay shows the highest GHG reduction cost in the west.

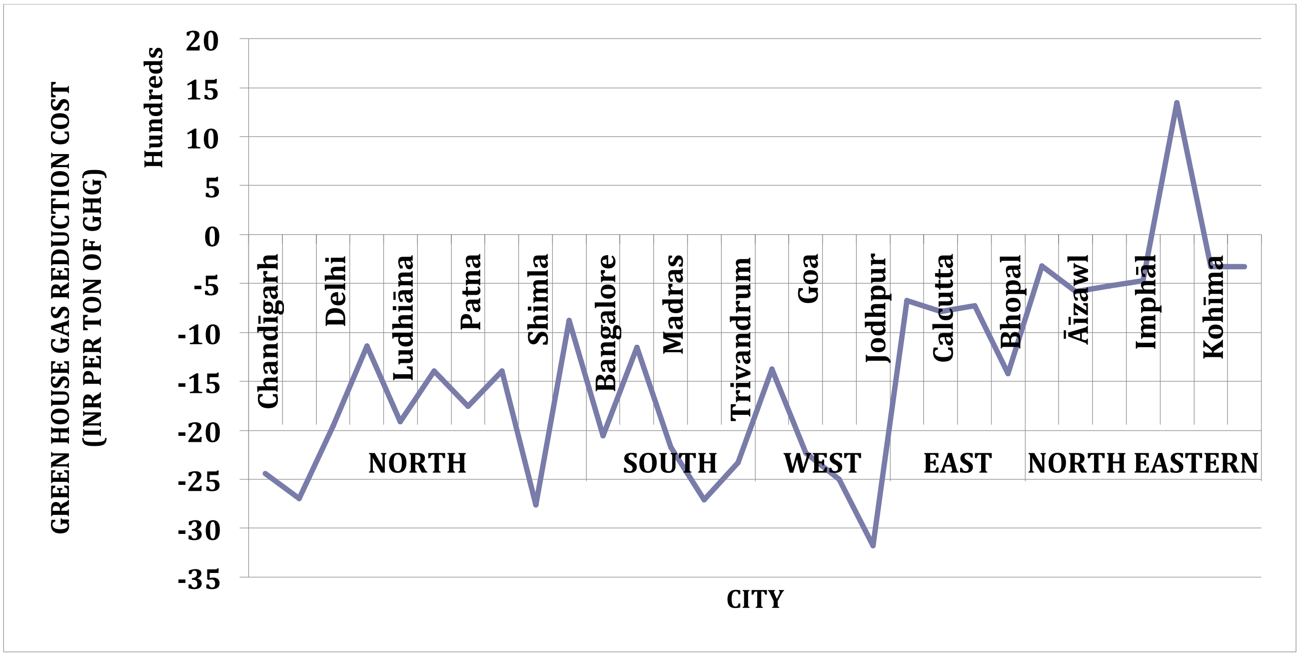

Figure 4.12 GHG reduction cost for different cities of India (INR per ton of GHG)

4.3.8 Carbon Credits

This project comprises of renewable energy technologies that supply electricity to and/or displace electricity from an electricity distribution system that is or would have been supplied by at least one fossil fuel or nonrenewable biomass fired generating unit. The project activity would substitute electricity generation in grid system, which is being fed primarily by fossil fuel fired power plants with a carbon neutral fuel (solar energy) for power generation. Thus, the GHG emissions which would have been produced from fossil fuel fired power units are avoided. Annual average over the crediting period of estimated reduction (tonnes of CO_2e) is 22,598.

4.4 Conclusion

A model is simulated for 31 major sites in India to study the viability of a 5 MW solar PV plant. Financial incentive announced in JNNSM has been considered as an input to the model. Solar radiation data is collected from NASA SSE. Model predicts various viability indicators like IRR, NPV, CoE, B-C ratio for 5 MW solar PV in 31 sites in India. A comparison of results is done and Jodhpur, Ahmedabad, Shimla and Dehradun are the best sites selected for setting up of 5 MW solar PV plants in India.

Chapter – 5

Application of Data to Assess Optimal CSP Sites and System Configurations

5.1 Introduction

The global energy demand is steadily increasing with the burgeoning world population and rising living standards. Solar thermal electricity technologies (CSP) can provide critical solutions to the global energy problem within a relatively short time- frame, and are capable of contributing substantially to GHG mitigation efforts (Quaschning, 2004; European Commission, 2007). Like the rest of the world, India faces formidable challenges in meeting its energy needs, and in providing adequate energy of desired quality in a sustainable manner and at competitive prices (GOI, 2006). India is located in the equatorial sunbelt of the earth, thereby receiving abundant radiant solar energy (Purohit and Garud, 2007). The country benefits from a sunny climate, in particular in its northwest region, which receives some 5.5 kWh/m^2 of solar energy daily (Nixon et.al, 2007). The Ministry of New and Renewable Energy (MNRE) is implementing a variety of programs to harness the enormous potential of solar energy in the country (MNRE, 2008). JNNSM was launched under the National Action Plan on Climate Change (NAPCC) by the Government of India on January 11, 2010 to create an enabling policy framework for the deployment of 20,000 MW of solar power by 2022. It further proposes a substantial investment in R&D and infrastructure to increase the share of solar energy within the total energy mix (GOI, 2008; MNRE, 2010).

To take advantage of the vast solar resource in the north-western part of India, one option that is currently of much interest is CSP. CSP is a technology by which sunlight is focused (concentrated) by mirrors or reflectors to heat a fluid in a collector at high temperature. The heated heat transfer fluid (e.g. pressurized steam, synthetic oil or molten-salt) flows from the collector to a heat engine where a portion of the heat (up to 30%) is converted to electricity (Jacobson, 2009). CSP technology utilizes four alternative technological approaches: parabolic trough, power tower, dish/engine and linear Fresnel reflectors. Trough systems use the mirrored surface of a linear parabolic concentrator to focus direct solar radiation on an absorber pipe running along the focal line of the parabola (Hang et.al, 2008). It is the most developed CSP technology with around 90% of total currently operating plants (more than 500 MW) in the world (Jacobson, 2009). This technology requires around 40000 m^2/MW land; while approximate water requirement is 2.9–3.5m^3/MWh (Jacobson, 2009). In the early 1990s, Luz International Ltd. installed nine parabolic-trough electricity generating systems totaling to 350 MW capacities in California's Mojave desert. These plants have been operating daily for up to 18 years, and as the year 2001 ended, the said plants accumulated to a total of 127 years operational experience (Herrmann et.al, 2004). Thus, parabolic trough technology has been chosen for this analysis since it is currently the most proven solar thermal technology.

There have been several attempts to select the best sites and optimize the performance of CSP plants in the world. Badran and Eck (2005) have discussed the use of Parabolic trough solar thermal (PTST) power plants for electricity production in Jordanian climate for two different sites: Amman and Ma'an. An analysis of the daily power output, direct normal irradiation and the efficiency for the two sites have been carried out. Bett and Dimroth (2009) did a study to identify the least cost feasible option for the installation of PTST plants. A parametric cost-benefit analysis has been carried out by varying parameters, namely: capacity, capital investment, operating hours, carbon dioxide emission trading system price, etc. Beerbaum and Weinrebe (2000) have compared the levelized cost of electricity (LCOE) for Solar Thermal Energy (STE) with the corresponding LCOE for the electricity generating options used at present. It was found that STE is an economically viable technology under favorable conditions, i.e. in areas with high insolation levels and availability of capital at low interest rates. Salvador et al. (2010) have used the probability-density function of irradiation in conjunction with screening models to evaluate the performance characteristics and costs of concentrating solar power plants. The methodology has been applied to Spain, and the analysis of the results shows that a solar energy production of 37 kWh/m^2/year for tower plants and 66 kWh/m^2/year for parabolic-trough ones define the approximate optimal working conditions for the mean DNI in Spain.

Broesamle et al. (2001) have used STEPS, an evaluation system for solar thermal power stations, to calculate the performance of such power stations as a function of direct solar radiation, geographical conditions (land slope, land cover, distance from cooling water resources, etc.), infrastructure (pipelines, electricity grids, streets etc.) and the configuration and performance of a selected solar thermal power plant concept. Montes et al. (2008) describe the influence of solar multiple on the annual performance of parabolic trough solar thermal power plants with direct steam generation (DSG). The reference system selected is a 50 MWe DSG power plant, with thermal storage and auxiliary natural gas-fired boiler. Zhihao et al. (2009) have developed a software tool called Heliostat Field Layout Design (HFLD) for heliostat field layout design and performance calculation. The simulation results from HFLD approximately agree very well with the published heliostat field efficiency data from Spain PS10. Purohit and Purohit (2010) have made a preliminary attempt towards the technical and economic assessment of concentrating solar power

(CSP) technologies in India. The preliminary results indicate that the use of CSP technologies in India make financial sense for the north-western part of the country (particularly in Rajasthan and Gujarat states). Following are some of the parameters which impact the design of CSP plants.

5.1.1 Technology Selection

Purohit and Purohit (2010) reported that large scale concentrating solar power systems have been developed worldwide for about 30 years and parabolic trough system is the most developed Concentrated Solar Thermal (CSP) technology. Technically, PTC is advantageous due to its ability to store solar thermal energy for use during non-solar periods and to dispatch when it is needed the most. TES allows PTC plants to achieve higher annual capacity factors ranging from 25% without thermal storage to 70% or more with it (TroughNet, 2010). There are two main types of molten salt thermal storage systems namely: indirect and direct molten salt thermal storage. With indirect molten salt thermal storage, solar thermal energy delivered by HTF (Heat Transfer Fluid) like Therminol oil from the collector field is transferred through a heat exchanger to molten salt which serves as the storage medium (Garemella et al, 2010). In direct thermal storage, a single fluid such as molten salt serves as both the HTF and the storage medium. It flows directly between the collector field pipes and thermal storage tanks (Figure 5.1).

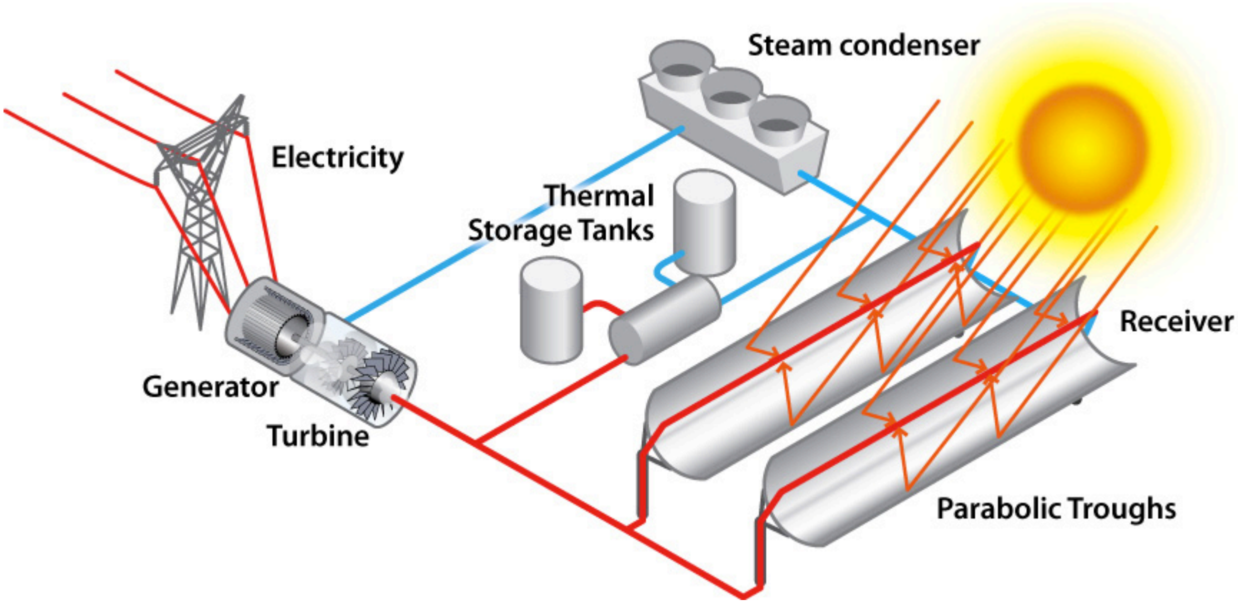

Figure 5.1 Schematic overview of parabolic trough solar plants with thermal energy storage

Molten salts can operate up to a higher temperature range of 450-500°C with low vapor pressures. It raises Rankine cycle efficiency by generating steam above 450°C for use in turbine (Garemella, 2010). Inorganic nitrate salts are the preferred storage media. Some of the commonly used nitrate salt mixtures include:

Solar salt which is a salt mix of 60% $NaNO_3$ - 40% KNO_3 with a freezing point of 120°C and costs 0.49 US$/kg (Kenisarin et al, 2010).

HITEC which is a ternary mixture of 40% $NaNO_2$ - 7% $NaNO_3$ - 53% KNO_3 with a freezing point of 120°C and costs 1.92 US$/kg (Kenisarin et al, 2010).

HITEC XL which is a ternary mixture of 48% $Ca(NO_3)_2$, 7% $NaNO_3$, 45% KNO_3 with a freezing point of 130°C and costs 1.19 US$/kg (Kenisarin, 2010 and Kearney 2004).

The unit cost for a two-tank indirect system parabolic trough plant is $30- $40/kWh (Price, 2003). In comparison, the cost of storage for large scale molten-salt power tower is less than $10/MW. Low thermal costs are a result of three times larger temperature rise in the Central Receiver Systems (CRS) compared to parabolic trough systems (Ortega, 2006). As the cost of thermal storage is reduced, future PTC could yield capacity factors greater than 70%, competing directly with future base load combined cycle or coal plants (TroughNet, 2010). Coupled with advancement in parabolic technology, its cost has been dropping fast. In an example of a power plant located in California, the cost of parabolic-trough generated electricity fell by 50% between 1985 and 1989 (from US$0.30/kWh to US$0.14/kWh) – a 14% drop each year (Taggart, 2008).

5.1.2 Model Selection

SAM is a comprehensive, solar technology system developed by NREL. It allows assessment of impact of variations in physical, cost, and financial parameters on the performance outcome (Blair, 2010). It produces comprehensive list of financial metrics for assessment, ranging from annual cash flow throughout project life, levelized cost of energy for the system, tax payments, net present value, to internal rate of return. The model can handle several types of financing and a variety of technologies (Blair, 2010). In addition, it performs simple cost breakdown in cost model, and hourly transient simulation in performance model. Furthermore, SAM can perform complex, near-instant sensitivity analysis, allowing a more holistic assessment of the system of interest (Blair, 2010). SAM's working procedure is illustrated in Figure 5.2.

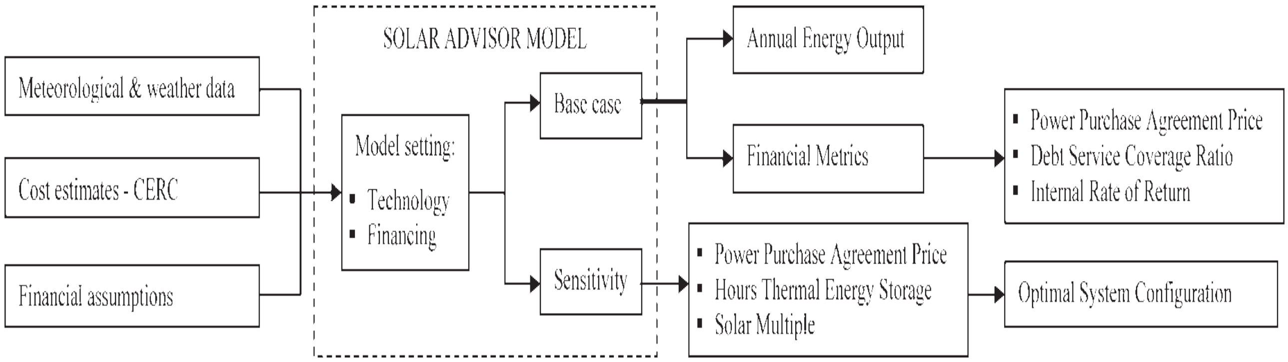

Figure 5.2 Schematic overview of working procedure of SAM (Jain et al, 2011)

5.1.3 Energy Storage

Adding Thermal Energy Storage (TES) provides several additional sources of value to a CSP plant (Sioshansi and Denholm, 2010). First, unlike a plant that must sell electricity when solar energy is generated, a CSP plant with TES can shift electricity production to periods of highest prices. Second, TES may provide firm capacity to the power system, replacing conventional power plants as opposed to just supplementing their output. Finally, the dispatchability of a CSP plant with TES can provide high-value ancillary services such as spinning reserves. Thermal storage system is not commonly employed in current parabolic trough plants, although there are some exceptions, like Andasol-1 in Spain, with 7.7 equivalent hours of indirect storage in two tanks of molten salts (Relloso and Gutiérrez, 2008).

The most significant recent work on molten salt storage comes from an experience in the Solar Two Project. This prototype facility, decommissioned in 1999, was a 10-MW power tower system using a nitrate eutectic molten salt as the HTF. The system contained 1.5 million kilograms of nitrate salt composed of a mixture of 60% $NaNO_3$ and 40% KNO_3, provided by Chilean Nitrate Corporation. This salt melted at 220°C and was thermally stable to about 600°C (Pilkington Solar International GmbH, 2000), thereby, emphasizing the prominent impact of the thermal storage in the role of CSP technologies (Shinnar and Citro, 2006). Extensive research and development are currently underway using various storage mediums that can enable this technology to materialize in an economically viable way (Ghobeity and Mitsos, 2009; Slocum and Codd, 2009).

5.1.4 Hybridization

This study addresses the challenge to develop a novel gas/hybrid design that combines high solar contribution and base load power demands that can meet throughout the year. The design integrates proven solar and fossil/storage technologies, thereby offering high reliability and low financial risk while promoting deployment of solar thermal power.

Hybridization means that the solar plant can also be operated by using some backup fuel, typically natural gas. All existing trough plants are hybrid plants. Sensible, cost-effective operation of a hybridized solar plant dictates that natural gas will be used periodically only to supplement electrical production. The fossil energy would likely be used only for economic dispatch during on-peak or mid-peak periods (Anders et al., 2005).

In the 1990s, Luz, the builders of the SEGS trough plants in California, proposed hybrid plant designs where solar steam would be used to supplement a combined cycle power plant. Kelly and coworkers (Kelly et al. 2009) examined the potential of such designs through a detailed analysis of power cycle performance using GateCycle. Recent work by the Electric Power Research Institute (EPRI) examined the optimum means for augmenting coal and natural gas combined cycle Natural Gas Combine Cycle (NGCC) plants with solar thermal energy (Kelly et al., 2001; Mishra et al.,1990).

Bohn et. al. (1995) evaluated a molten salt power tower hybrid design that provides preheated combustion air to a conventional NGCC power plant. Three plants of capacities (30, 100 and 300 MWe) were examined and compared with a solar-only 100 MWe plant and with a NGCC plant of similar capacity. The greatest downside to the use of natural gas in hybrid fashion is the argument that it would be better burned in a dedicated combined-cycle power plant. A modern NGCC plant can achieve thermal cycle efficiencies greater than 55% (heat rate less than 6200 BTU/kWh); whereas a parabolic trough plant has a thermal cycle efficiency of less than 40%. The use of small amounts of gas backup may be justified by the investment in the solar plant infrastructure, but the economics of burning natural gas in auxiliary boilers falls rapidly as gas consumption increases (Kelly et al., 2000).

5.2 Assumptions for base case 100 MW trough plant

SAM offers physical and empirical options for design of PSTS. Empirical model in SAM is preferable when the plant is similar in configuration to Solar Energy Generation Systems (SEGS) plants and for running quick simulations, depends on the empirical performances curves of SEGS. Physical trough option is based on heat and mass transfer equations and is selected for this study (SAM, 2011). Trough plant steam cycle performance was modeled in SAM using Jodhpur, Rajasthan as the reference site. 800 W/m^2 is determined as the reference DNI for designing solar parabolic trough plants. Solar multiple of one is used in the base case scenario. A solar multiple of one is the aperture area required to deliver sufficient thermal energy to the power cycle to drive it at its nameplate capacity under design conditions. The solar multiple is useful for optimizing the solar field size for a given power cycle capacity and location.

Analysis has been performed for CSP trough plant having a solar field area of 382 acres (1,545,899 m^2) with eight individual solar collector assemblies (SCA) per loop. Each SCA has 12 mirror modules. VP-1 is selected as the heat transfer fluid (HTF) that will circulate through the loops. The various technical parameters and design considerations used in SAM to deduce plant performance and cost are listed in Table 5.1.

Table 5.1 Technical parameters and design consideration used in SAM (SAM, 2011)

Solar field parameters	Values
Solar multiple	1
Irradiation at design	800 W/m^2
Heat transfer fluid	
Field HTF	VP-1
Minimum field flow velocity	0.356106 m/s
Maximum field flow velocity	4.9655 m/s
Land Area	
Solar field area	382 acres
Design point	
Number of loops	137
Single loop aperture	3762.4 m^2
Total aperture	515449 m^2
Field thermal output	294.118 MWt
Single loop configuration	
Number of SCA/HCE assemblies per loop	8
Collector (SCA)	
Configuration	Solargenix SGX – 1
Reflective aperture area	470.3 m^2
Aperture width of total structure	5 m
Length of collector assembly	100 m
Number of modules/assembly	12
Average surface-to-focus path length	1.8 m
Piping distance between assemblies	1
Receiver/HCE	
Configuration	Schott PTR 70
Total weighted losses	166.25 W/m^2
Power cycle	
Design gross electrical output	111 MWe

Estimated gross to net conversion factor	0.9
Estimated net output at design (nameplate)	100 MWe
Design inlet temperature	391°C
Design outlet temperature	293°C
Boiler operating pressure	100 bar
Fossil backup boiler LHV efficiency	0.9
Cooling condenser type	Evaporative
Parasitics	
Balance of plant parasitic	0.02467 MWe/MW cap
Auxillary heater, boiler parasitic	0.02273 MWe/MW cap
Piping thermal loss coefficient	W/m^2

The 100 MW PTC solar power plant has three major components: a solar field, a power block, and a thermal energy storage system. In this analysis, duration of thermal energy storage will be varied from zero hour to a maximum of 12 hours. The effect of this variation will be studied against the Power Purchase Agreement (PPA) price and solar multiple. The base case for this analysis involves a 100 MW trough plant with no energy storage operating at a capacity factor of 15.6%. It is significantly lower than the capacity factor of 23% assumed by the Central Electricity Regulatory Commission (CERC) (CERC, 2010).

In this study, capital cost estimates are taken from CERC regulations (CERC, 2010). In particular, capital cost estimate for a 100 MW PTC solar power plant would include cost for site improvement, solar field, power block, heat transfer fluid system, thermal storage system, and other costs related to engineering, design, procurement, construction, and management, etc., totaling approximately to 270.5 million USD.

In addition to the above cost assumptions, other financial parameters are also included in the analysis. CERC assumptions have been used for determining economics of the project (CERC, 2010). In order to determine the cost of electricity from this plant, a 25-year cashflow analysis is performed. It is assumed that the power plant is financed with 70% debt fraction at 13.39% p.a. interest rate in 10 years. Straight line depreciations are set at seven for 10 years and 1.33 for next 15 years, while real discount rate is set at 15.97%. Inflation rate is assumed to be 2.5% p.a.

The above data, information, and assumptions are input into SAM. The selected technology option would be concentrating solar power with parabolic trough system. The financing option in the model is chosen as Utility and Independent Power Producer (IPP), implying that the project covers costs through electricity sale revenues. SAM yields electricity outputs, PPA prices, debt service coverage ratio (DSCR), and internal rate of return (IRR).

5.2.1 Assumptions for hybridization case

When the system includes thermal energy storage or fossil backup, SAM uses a different dispatch strategy for up to eight different dispatch periods. The present study takes a 10% interval starting from zerio and going up to 100 % percentage hybridization. When the fossil fill fraction is greater than zero for any dispatch period, the system is considered to include a fossil-fired boiler that heats the heat transfer fluid before it is delivered to the power cycle. The fossil fill fraction defines the backup boiler output as a function of the thermal energy from the solar field (and storage, if applicable) in a given hour and the power cycle design gross output. LCOE decreases with increase in hybridization and there has to be a limit on hybridization to maintain an optimum solar content. Optimum solar content is estimated by rate of change of annual units of electricity generation with different hybridization percentages.

5.3 Assessment of Concentrating Solar Power Potential in India based on Satellite Direct Normal Irradiation Data

This section focuses on the assessment of CSP potential in India based on high resolution NREL satellite direct normal irradiation data and uses solar advisory model to optimize and measure the performance of CSP plants. Preliminary screening of sites is done based on the climate and geographical parameters and 25 sites are shortlisted based on these criteria. Detailed solar radiation analysis is done for all the 25 shortlisted sites is India. Several techno-commercial parameters are discussed to determine the performance and viability of 100 MW PSTS plant at 25 sites.

This section studies the techno-commercial feasibility of a 100 MW parabolic trough solar thermal (PTST) power plant at 25 shortlisted sites in India. An analysis of the impact of reference direct normal irradiation (DNI) on solar multiple (SM), on yearly electricity production and levelized cost of electricity (LCOE) for 25 sites has been carried out. Solar multiple is defined as the ratio of the power capacity of the collection field to the capacity of the power block. The analysis is based on the SUNY model estimates the global and direct irradiance at hourly intervals on the 10-km grid for entire India.

Initial screening of sites is done by using the Geospatial Toolkit (GsT), a map viewer developed by NREL (NREL, 2011). GsT product provides composite land cover classification at a cell resolution of ~10 km, allowing for high-resolution screening of potential CSP sites in India. Geomorphological features like sand dunes, rocky outcrops, salt flats, and glaciers have been excluded, as were areas with terrain slope greater than 5%. Site selection criteria is kept stringent, only allowing construction on ground that is bare or covered with sparse or herbaceous vegetation and excluding reserves, parks, and other protected areas.

Reference DNI is an important parameter in the design of the 100 MW parabolic trough plant in the SAM. The 'reference' DNI value is a user-specified input to SAM that determines the size of the solar field for a given solar multiple. A good estimate is the maximum hourly DNI incident on the solar field during the year, which can be approximated given hourly DNI and latitude (SAM, 2011). DNI hourly data for the selected 25 sites have been obtained from hourly data released by NREL (NREL, 2011). The SUNY model estimates the global and direct irradiance at hourly intervals on the 10-km grid for the entire of India, as shown on India's solar maps. The data is produced using visible images from a Meteosat satellite. DView software in SAM is used to find the maximum value of Collector_DNI-x-CosTh. The maximum incident DNI value is used for irradiation at design.

5.3.1 Results and Discussion

Preliminary screening of sites is done based on the criteria defined in Table 5.2 and 25 sites are shortlisted based on these criteria (Table 5.3). These sites thought to be representative of potential CSP sites are identified by first restricting to stations with average daily DNI greater than 4.0 kwh/m2. For each site, SAM is used to simulate the cost-minimizing design and performance for a parabolic trough CSP plant. Detailed modeling in SAM was performed for these sites, and the results are used to construct the cost benefit analyses.

Table 5.2 Criteria for site screening by NREL geospatial kit (NREL, 2011)

Resource – DNI (kwh/m^2/day)	
Minimum value	4.0
Maximum value	9.0
Exclude Protected areas	Yes
Landuse	Barren or Sparsely or Cropland/Grassland Mosaic
Slope (%)	
Minimum value	0.0
Maximum value	5.0

Table 5.3 Coordinates and DNI for 25 shortlisted sites in India

Site Name	State	Latitude (^{o})	Longitude (^{o})	DNI (Kwh/m^2/year)	Elevation (m)
Ahmedabad	Gujarat	23.07	72.63	1878	55
Akola	Maharashtra	20.7	77.03	1799.1	282
Amritsar	Punjab	31.38	74.52	1755.9	234
Aurangabad	Maharashtra	19.88	75.33	2192.5	581
Barmer	Rajasthan	25.75	71.38	1971.3	194
Belgaun	Maharashtra	15.52	74.32	1769.3	753
Bhopal	Madhya Pradesh	23.28	77.35	2028.7	523
Bikaner	Rajasthan	28	73.3	2113.2	224
Chitradurg	Karnataka	14.13	76.27	1617.7	733
Delhi	Delhi	26.23	78.25	1671	216
Gwalior	Madhya Pradesh	29.17	75.73	1685.1	207
Hisar	Haryana	17.45	78.47	1614.8	221
Hyderabad	Andhra Pradesh	22.72	75.8	1776.8	545
Indore	Madhya Pradesh	26.82	75.8	2388.1	567
Jaipur	Rajasthan	26.9	70.92	1987.8	390
Jaiselmar	Rajasthan	22.47	70.02	2114.8	242
Jamnagar	Gujarat	26.3	73.02	1926.3	20
Jodhpur	Rajasthan	25.15	75.85	2262.3	217
Kota	Rajasthan	15.5	78.03	1836	274
Kurnool	Andhra Pradesh	26.87	80.93	1759.9	281
Lucknow	Uttar Pradesh	21.1	79.05	1638.1	111
Nagpur	Maharashtra	28.58	77.2	1858.4	310
Rajkot	Gujarat	22.3	70.78	2262.2	138
Tiruchirapalli	Tamil Nadu	10.77	78.72	1877.7	88
Saharanpur	Uttar Pradesh	29.85	77.88	1737.5	274

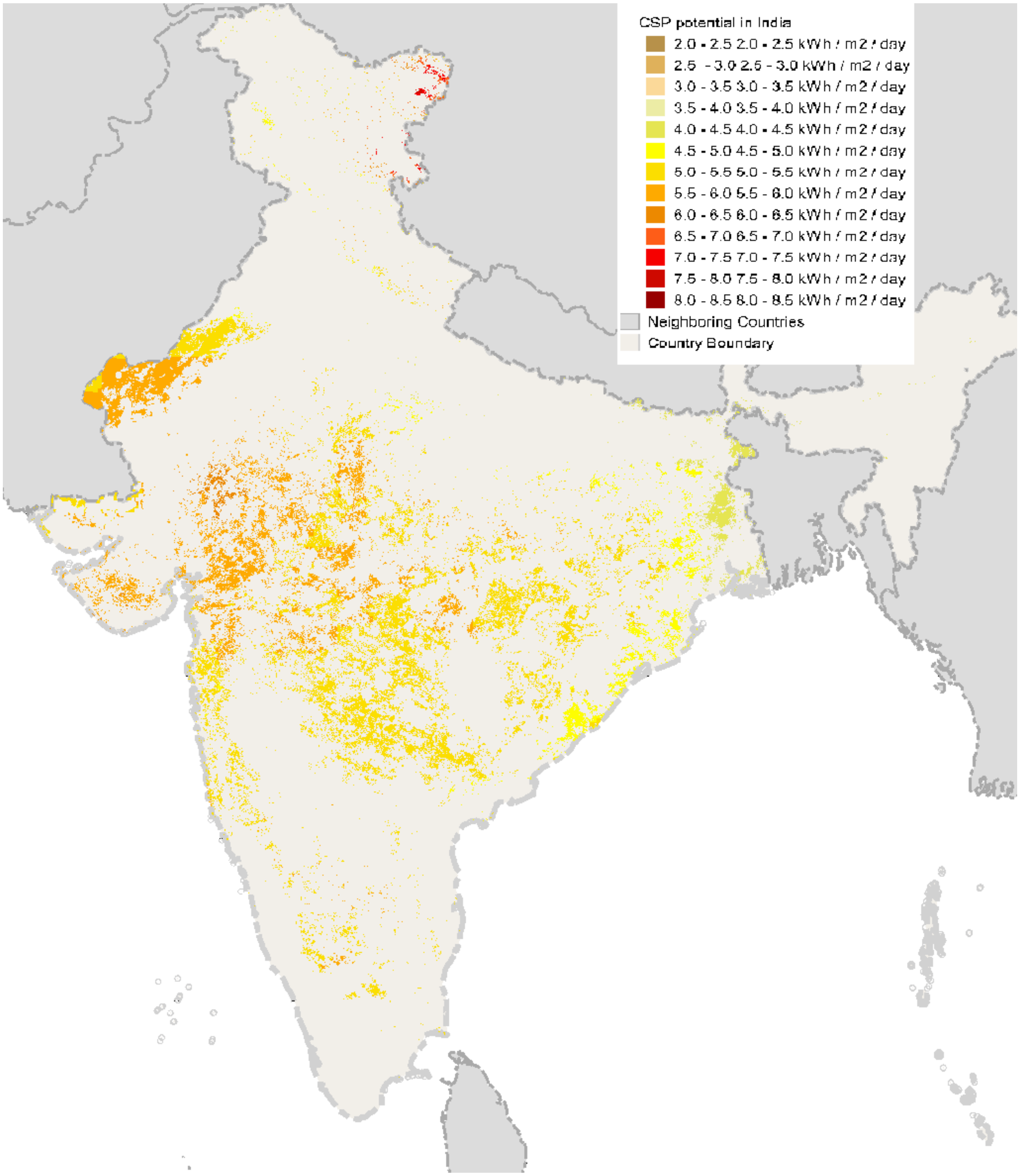

Figure 5.3 Map for CSP potential regions in India (Simulation results using Geo spatial tool kit)

Techno-commercial parameters for 25 sites

DNI: Figure 5.3 illustrates DNI values for northern, southern, western and central parts of India. DNI varies from a minimum value of 1600 Kwh/m^2/day at Hisar (Haryana, Northern India) and Chitradurg (Karnataka, Southern India) to a maximum value of 2400 Kwh/m^2/day at Indore (Madhya Pradesh, Central India). It can be observed from the Figure 5.4 that western region of India shows higher DNI values compared to other parts of India. Jodhpur (Rajasthan) and Rajkot (Gujarat) receive the highest DNI dosage of about 2300 Kwh/m^2/year in the entire western region. Northern India receives insignificant DNI with a maximum DNI value of only 1750 Kwh/m^2/year for Saharanpur. Annual DNI for southern India is observed to vary from 1600 Kwh/m^2 in Chitradurg to 1900 Kwh/m^2 in Tiruchirapalli. There are several other locations which receive fairly large amount of radiation as compared to many parts of the world especially in Japan, Europe and the US, which have the highest development and deployment of solar technologies. However, there is little solar radiation literature available in India to estimate the impact of solar radiation on viability of CSP at different sites.

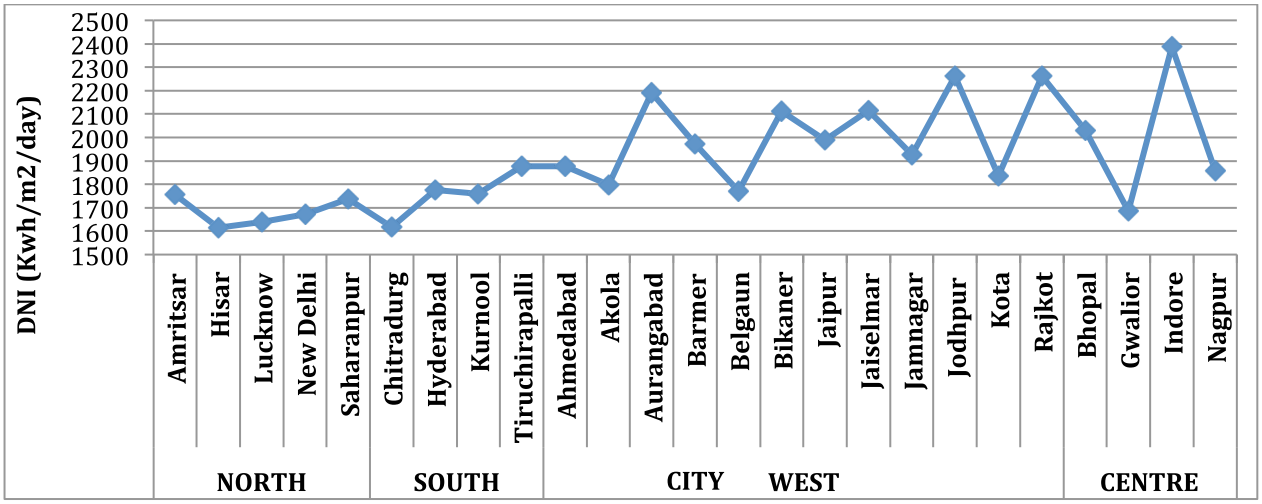

Figure 5.4 Direct Normal Irradiation (DNI) profile for shortlisted 25 CSP sites in India

Financial parameters: The key lever that has been designed to drive the participation of solar generating companies is a feed-in tariff which has been coupled with a unique power sale structure (CERC, 2010). Table 5.4 lists the assumptions and incentives announced by Centre Electricity Regulatory Commission (CERC) for setting up CSP power plants in India. Project financial analysis has been carried out considering debt equity ratio of 70:30. CERC assumptions have been used for determining economics of the project. Total equity and debt amount per megawatt are assumed to be INR 450 and 1250 lac, i.e, 45 million and 125 million, respectively. Interest rate at debt part has been considered at 13.25%. Total project cost has been estimated at INR 1500 lac (150 million) per megawatt. It does not include storage, hybridization or dry cooling technologies. The total installed cost for the solar hardware is also based on CERC cost assumptions (Table 5.4). CERC provides an interest subsidy of 12.75 % per annum on the working capital.

Table 5.4 CERC cost assumptions for CSP plant in India

Parameter	Value	Unit
Analysis period	25	Years
Debt fraction	70	%
Loan rate	13.4	% p.a.
Loan term	10	Years
Capital Cost (INR)	15	Crores/MW
Capacity	100	MW
Discount rate	15.6	%

Annual energy production: Figure 5.5 represents the annual energy (MU) produced by cities in different parts of India. Indore, situated in Madhya Pradesh, generates the highest annual output of approximately 169 MU, indicating availability of large solar resource (DNI) in this part of central India. Lowest annual energy output (90 MU) corresponds to Hisar located in the state of Haryana, Northern India. Jodhpur (Rajasthan) and Rajkot (Gujarat) in western India record high annual energy production values of 158 MU and 159 MU, respectively. In Figure 4.5, all the cities representing western region of the country depict higher energy generation values compared to the rest of the regions.

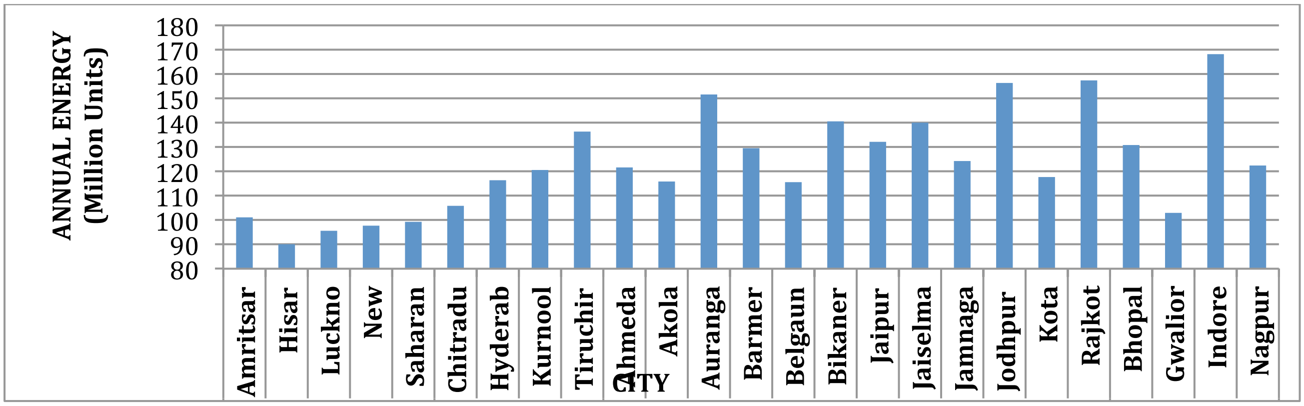

Figure 5.5 Annual energy production (MU) for CSP sites in India

Capacity factor: Figure 5.6 shows annual capacity factors achieved by cities located in different regions of India. Highest capacity factor of 19% is attained by Indore situated in central India. Hisar in northern India is limited to a capacity factor of 10 %, which is the lowest among all the cities. Jodhpur and Rajkot in the western region of India achieved high capacity factors of almost 18%, suggesting high normal irradiance received by these parts of the western region.

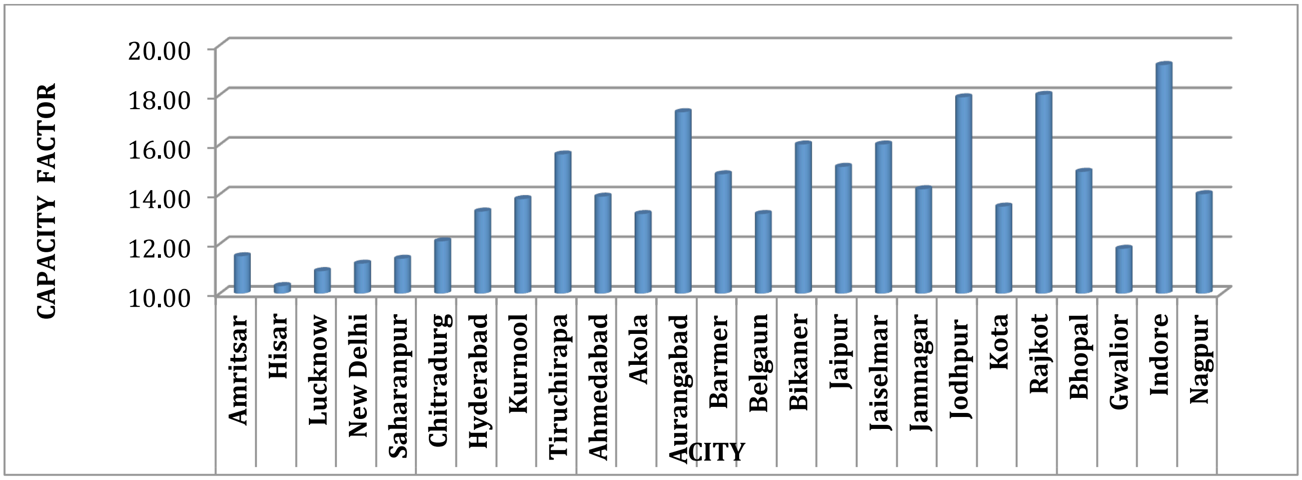

Figure 5.6 Capacity factor (%) for CSP sites in India

LOCE: Average cost of electricity generation for various cities is illustrated in Figure 4.7. Indore corresponds to minimal value of LCOE (32.5 cent/kWh), indicating the project to be most economically viable if implemented here. Jodhpur and Rajkot in western India correspond to the second lowest LCOE value of 35 US cent/kWh. It can be observed from the Figure 5.7 that all the cities located in northern India have higher LCOE values than the cities located in other parts, with

Hisar accounting for the highest LCOE value of 61 US cent/kWh.

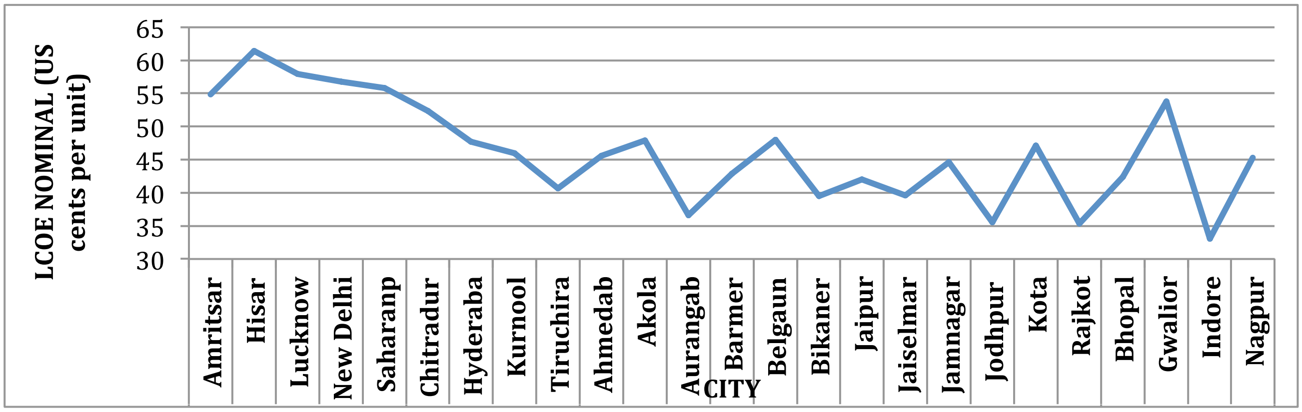

Figure 4.7 LCOE (US cents per unit) for CSP sites in India

5.4 Site Selection and Optimizing the Cost and Performance of Parabolic Trough Solar Plants with Thermal Energy Storage in India

Due to its intermittent nature of solar energy (PV and CSP), there remains a number of issues, the most important one being thermal energy storage (TES) (N'Tsoukpoe, 2009). The main purpose of TES is to store solar thermal energy for use during non-solar periods which then determines a solar plant's operating hours. It is reported that together with plant size and capital expenditure, plant operating hours is a parameter that determines project's viability (Poullikkas, 2009). It has been found that for plants with higher capacity and higher degree of storage, investment appears to be more attractive in the Mediterranean region (Poullikkas, 2009).

The present study explores the feasibility of developing a 100 MW solar thermal power plant using parabolic trough concentrated technology (PTC) with different degree of TES at Jodhpur, Rajasthan, India. The feasibility will be assessed using meteorological and solar radiation information for Jodhpur, Rajasthan and general Indian customized cost estimates for PTC solar power plant. System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL), under the U.S. Department of Energy, has been used in this assessment. The study performs sensitivity analysis to measure the impact of uncertainty in solar radiation on project economics and performance including LCOE and CUF of the 100 MW PTC plant.

5.4.1 Site selection

Rajasthan is a state in the north-western part of India with an area of about 342,000 sq. km. It has varied topography and has a wide range of climatic conditions varying from extremely dry and arid in the western Thar desert to humid in the eastern and south-eastern part of the state. It is one of the driest and hottest states in India with an average maximum temperature of 42^0C during summer. The western desert area has an average annual rainfall of about 100 mm (Chaurey et al., 2005).

Most parts of the state experience about 250 to 300 sunny days in a year. Jodhpur city (Latitude 26.3^0, Longitude 73.02^0) in the state has been identified as one of the cities having high potential for development of solar power plant (Figure 5.8). It receives more than 2100 kWh/m^2 of annual global radiation, which is the highest in India (Garud, 2010) and hourly average direct normal irradiation ranging from 175 Wh/m^2 to 375 Wh/m^2 (Figure 5.9). The peak load and electricity energy requirement of the state in 2021-2022 is predicted to be 15 GW and 92,377 GWh, respectively (Central Electricity Authority, 2009).

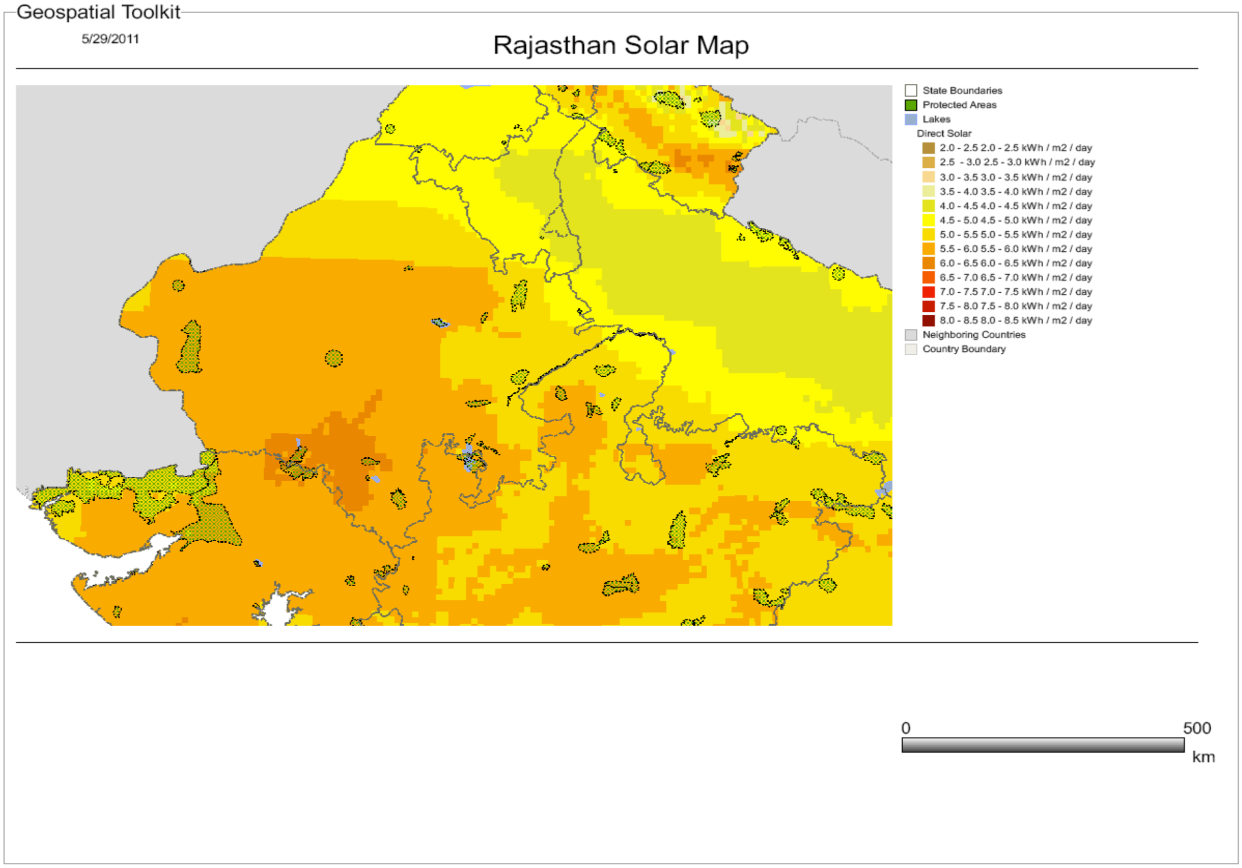

Figure 5.8 Solar Map of Rajasthan, derived from NREL dataset (NREL 2011, TroughNet, 2010)

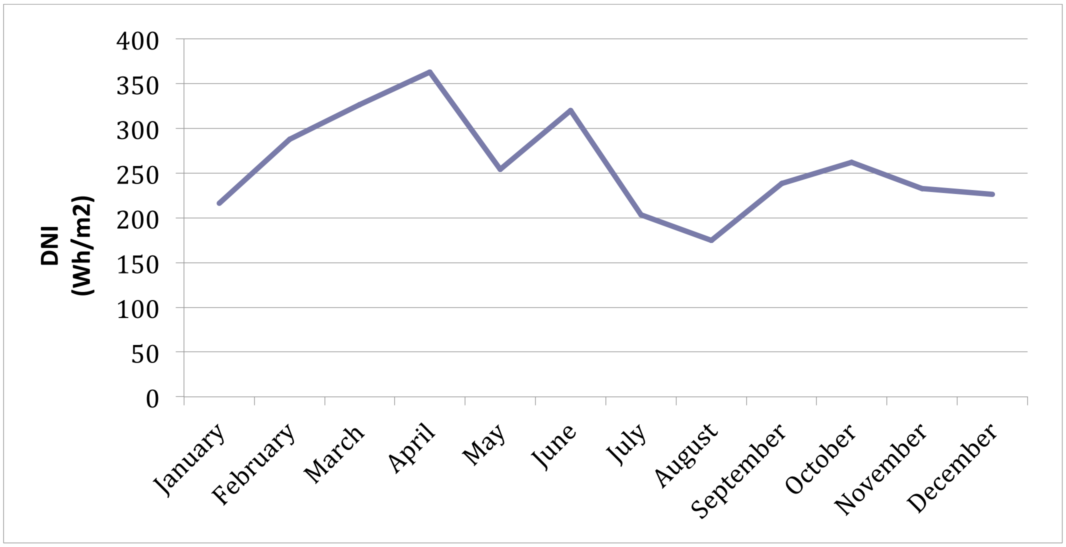

Figure 5.9 Long term monthly average direct normal solar irradiance in Jodhpur, Rajasthan (U.S. Department of Energy,2012)

Jodhpur, Rajasthan weather data was sourced from the US Department of Energy (U.S. Department of Energy, 2012). Jodhpur weather file is derived from the Indian Society of Heating, Refrigerating and Air-Conditioning Engineers (ISHRAE). ISHRAE has developed weather files for use with building energy performance simulation programs for 58 locations in India in TMY2 format. The data was in the form of EPW file which can be directly used in SAM. In addition to daily average direct normal irradiation (DNI) information (Figure 5.9), daily average of dry bulb temperature is presented in Figure 5.10 while daily average of relative humidity is shown in Figure 5.6.

In general, daily average DNI is higher in the earlier half of a year, increasing gradually from January to peak at the end of April, dropping to lowest measure in early May before it rises to another maximum in mid-June (Figure 5.9). Although local maxima in daily average DNI occur in July and mid October, these measures are only about 75% of the maximum values measured earlier in the year. It corresponds to the summer season in April to June and monsoon (rainy) season in July to September. Monthly average dry bulb temperature appears to follow similar pattern to that of daily average DNI in the first half of the year. It peaks in early June at about 37^0C, and then decreases gradually to a minimum value of about 12^0C in December (Figure 5.10).

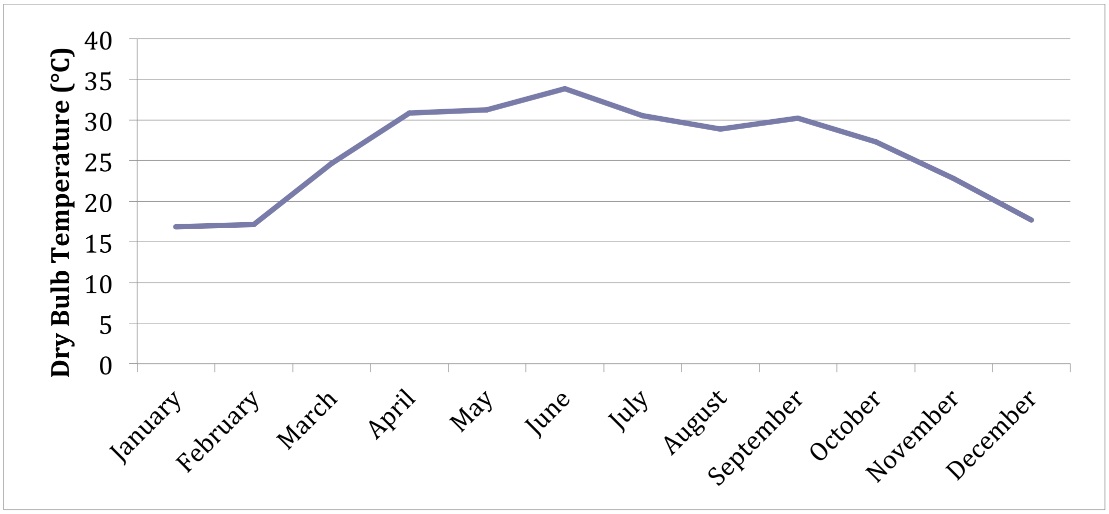

Figure 4.10 Monthly average dry bulb temperatures (^{o}C) in Jodhpur, Rajasthan (U.S. Department of Energy, 2012)

There is a wide range in monthly average relative humidity (RH) in Rajasthan with a minimum at 20% and a maximum at about 85%. Highest fluctuation in RH occurs at the end of April and early May. In general, Rajasthan experiences dry period with low RH in the first few months of the year, before it gets more humid from May until August which could coincide with the monsoon period when ocean wind brings humid air into the region (Figure 5.11).

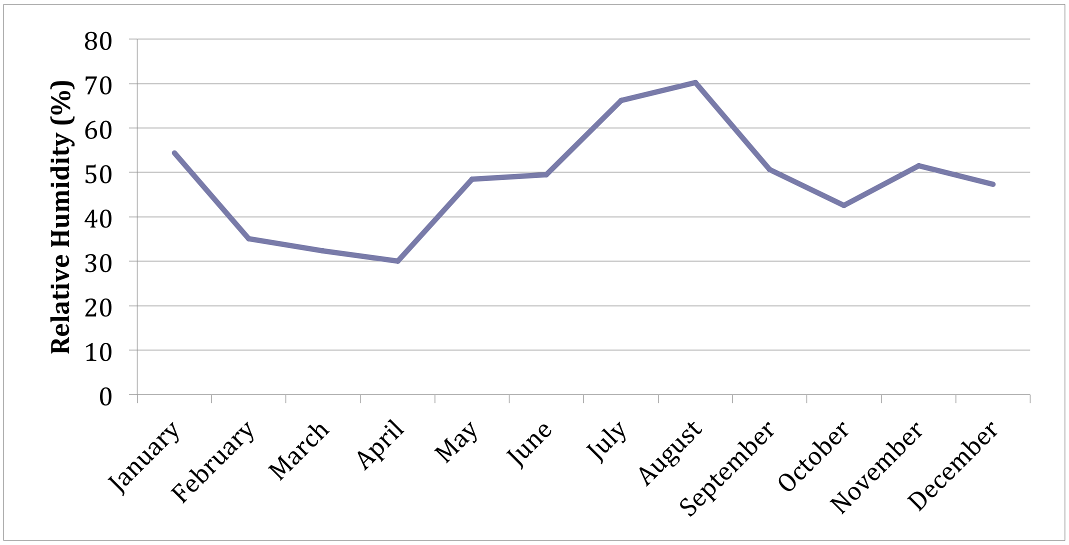

Figure 5.11 Monthly average relative humidity (%) in Jodhpur, Rajasthan (U.S. Department of Energy,2012)

5.4.2 Results and Discussions

Total annual energy output for the proposed plant in the study is 145 million kWh, but there are significant variations in monthly electricity output (Figure 5.12). Monthly electricity output corresponds to monthly average DNI. Apparently, net output increases gradually from the beginning of the year, peaking in April, dropping in May, before peaking again in June. Without energy storage, minimum monthly output is approximately 6.7 million kWh, while the maximum figure reaches 20.2 million kWh. This variation is due to onset of monsoons (rainy season) in July and August. There is a sudden drop in DNI due to the increased cloudiness associated with the monsoon. This results in drop in power generation. The result is also consistent with other weather parameters described in the figures above.

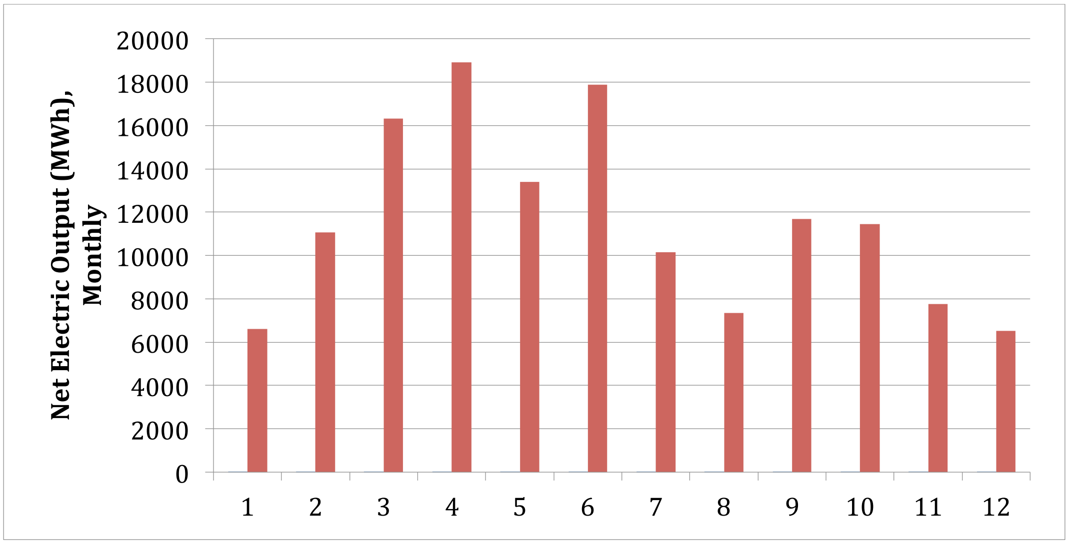

Figure 5.12 Monthly electricity output in base case (kWh)

In the base case without thermal storage, PPA price is calculated at 34.17 US cents/kWh. With CERC (2010) financial assumptions, the DSCR calculated is 1.16 and the IRR is 15%. The resulting financial metrics fall within acceptable range of specified feed-in tariff indicated by the Indian Government in India Solar Guidelines, implying that the system configuration in base case is financially feasible. In addition, the project may give average returns for the investment. With the main revenue for this plant stemming from sale of electricity, the project expects simple payback of over 10 years and discounted payback period of over 14 years (Figure 5.13). After tax cash flow jumps at the end of year 10 indicating the point when debt is retired.

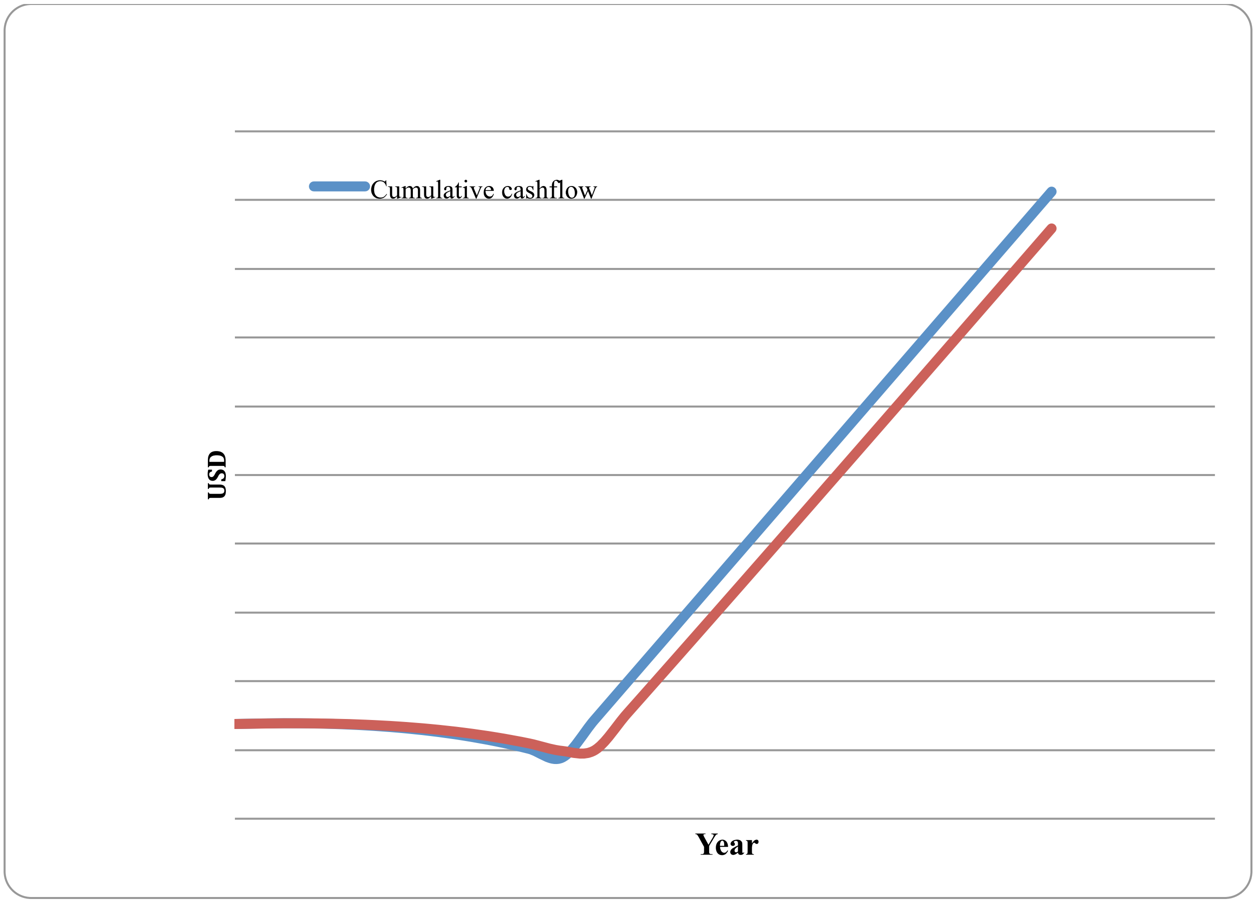

Figure 5.13 Simple and discounted cumulative project's cashflow

The perceived minimal loss between the plant’s major components and the gap of about 13.6 million kWh between the highest and lowest monthly and daily outputs indicate the need for thermal storage of longer duration, possibly in months or seasons, to maximize the utilization of solar energy located in Rajasthan plant.

Optimization of PTC is being done by running different simulation scenarios for TES and solar multiple. The higher the solar multiple, the larger the solar field needs to be in order to meet thermal requirement of steam generators. Consequently, it increases the initial capital cost and a larger field area is required. In this study, the solar multiple is varied from one to three while thermal energy storage duration changes from zero to 12 hours. PPA prices are calculated against various value of solar multiple and energy storage duration for identification of the optimal system configuration.

It can be seen from Figure 5.14 that when a solar field’s thermal capacity just meets requirement of steam generators, the value of solar multiple is one (1). When the duration of thermal energy stored is increased, the cost of TES increases. In order to cover the costs, higher PPA price is required, if solar multiple remains constant. At higher solar multiples, PPA price drops with increasing energy storage duration to a lowest point corresponding to certain storage duration before it increases. In particular, PPA price is found to be lowest at about 31.4 US cents/kWh corresponding to solar multiple of two- and three-hour of thermal energy storage, thus increasing the project returns significantly. This is the best case scenario for optimizing the parabolic trough with thermal energy storage in India. Similarly, at solar multiple of three, lowest PPA price of about 32.3 US cents/kWh occurs when thermal energy is stored for nine hours. In this scenario, capital cost of plant increases without any significant decrease in the PPA price, hence, not recommended as a design option for the solar power plant. Increasing thermal energy storage duration along the optimal PPA price contour will lead to increased solar multiple and vice versa. In any case, such increase will result in increased cost for the plant owner and operator, undermining financial viability of the plant.

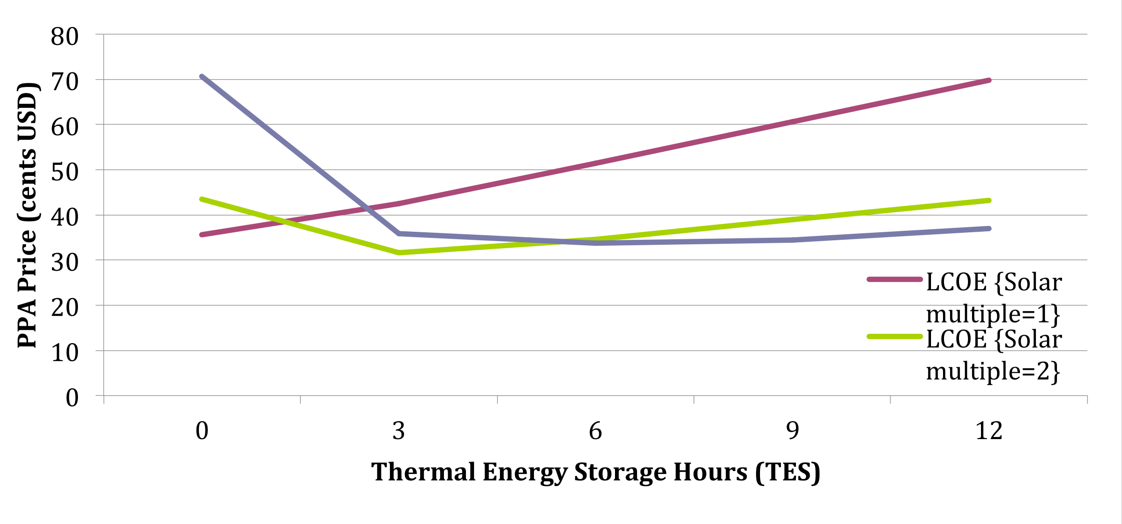

Figure 5.14 Simulation Scenarios for PPA price vs hours of TES

Errors in DNI input data sets vary on monthly and yearly basis and depends on the type of equipments used for measurement and modelling techniques. The DNI input data sets are likely to have uncertainties of as much as 10% (U.S. Department of Energy, 2012). Present study recognizes the uncertainty in DNI input values and its impact on the performance and design of PTC plants (U.S. Department of Energy, 2012). A sensitivity analysis of these uncertainties to the study results ares provided. Figure 5.15 shows the impact of DNI uncertainty on LCOE and capacity factor of a 100 MW PTC plant. Curve representing LCOE exhibits an inverse relation with DNI. Capacity factor curve, on the other hand, increases with increase in DNI. When DNI increases by 3.07% (1986 kWh/m^2 to 2058 kWh/m^2), LCOE undergoes a decline of 4.64% while capacity factor values show a 4.31% increase. The decrease in LCOE and percent increase in capacity factor becomes uniform when DNI increases from 2058 to 2074 kWh/m^2. Decrease in LCOE is a consequence of the fact that profitability of CSP project lies on electricity production, which in turn is dependent on solar irradiation. LCOE depicts a decrease of 2% at DNI value of 2096 kWh/m^2, while capacity factor rises by 2% at the same DNI value. It is determined from this figure that uncertainty in DNI uncertainly has a direct influence on LCOE and capacity factor.

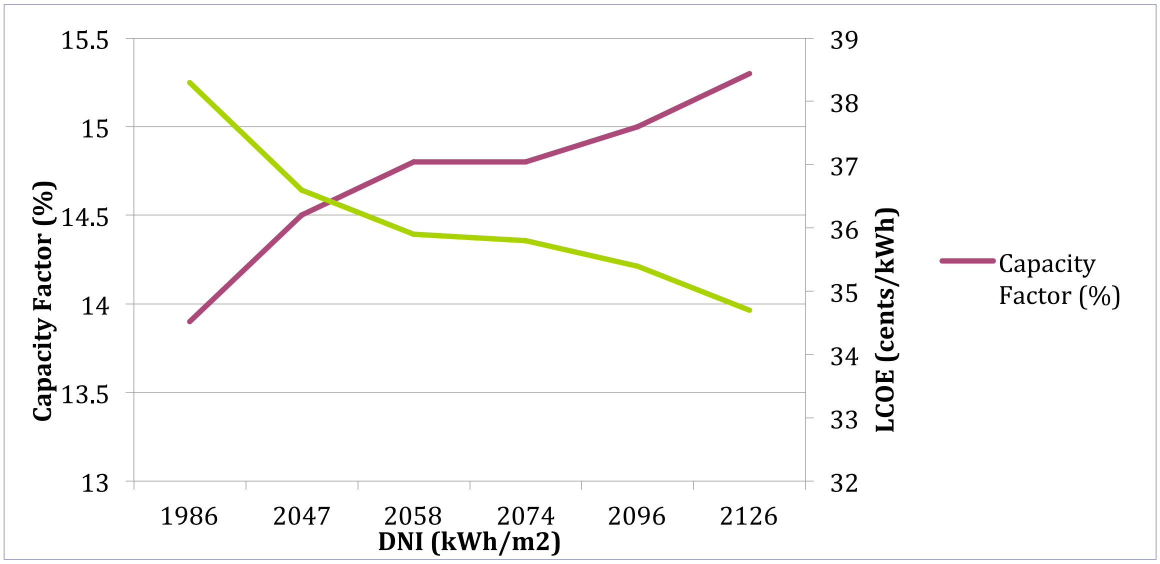

Figure 5.15 Impact of DNI sensitivity on LCOE and capacity factor (CF)

This section indicates that a 100 MW parabolic trough concentrating solar thermal power plant without thermal energy storage is a viable option for Jodhpur, Rajasthan if electricity can be sold at a PPA price of 34.17 US cents/kWh, which is within the range specified by the Indian government's feed-in tariff for solar energy. The system can be optimized for better financial performance by designing with solar multiple of two and at least three hours of thermal energy storage. In such a case, PPA price drops to about 31.4 US cents/kWh, increasing the plant's financial viability. Although thermal energy storage has been incorporated into the system, in this study, the TES system is limited today. Sensitivity analysis is done to measure the impact of solar radiation on project economics and performance. The variation in measurement and prediction of solar radiation has a direct impact on the levelized cost of electricity and capacity factor of the 100 MW parabolic trough plant. Decrease in LCOE is a consequence of the fact that profitability of CSP project lies on electricity production, which in turn is dependent on solar irradiation. It is determined from sensitivity analysis that uncertainty in DNI uncertainly has a direct influence on LCOE and capacity factor.

5.5 Optimization Studies for Hybrid and Storage Designs for Parabolic Solar Trough Systems with the System Advisor Model (SAM)

This section examines different plant designs including two solar-only plants (differing in solar multiples) without storage or hybridization, solar-only plant with different hours of storage capacity, and a hybrid solar trough plant. The usual size of parabolic trough solar thermal plants being built at present is approximately 50 MWe (Montes et al., 2009). The reference system chosen for this study is a 100 MW parabolic trough plant. An optimization of the solar field size has been carried out for Jodhpur in Rajasthan. Jodhpur, Rajasthan is chosen as the reference site since it benefits from high DNI values or solar resource which is a pre-requisite for CSP projects. The present study evaluates the influence of solar multiple on the annual electricity generation and LCOE of a 100 MW trough plant without storage and also on a system integrated with different hours of storage. This study also examines the effect of different hybridization percentages on annual output and LCOE of hybrid trough plant with the help of SAM. The objective is to provide a combination of optimal solar multiple, hours of storage and hybridization percentage for construction of CSP plants in Rajasthan, India on the basis of this evaluation.

5.5.1 Results and Discussion

(i) Solar stand alone plant with solar multiple 1 without storage and hybridization (base case)

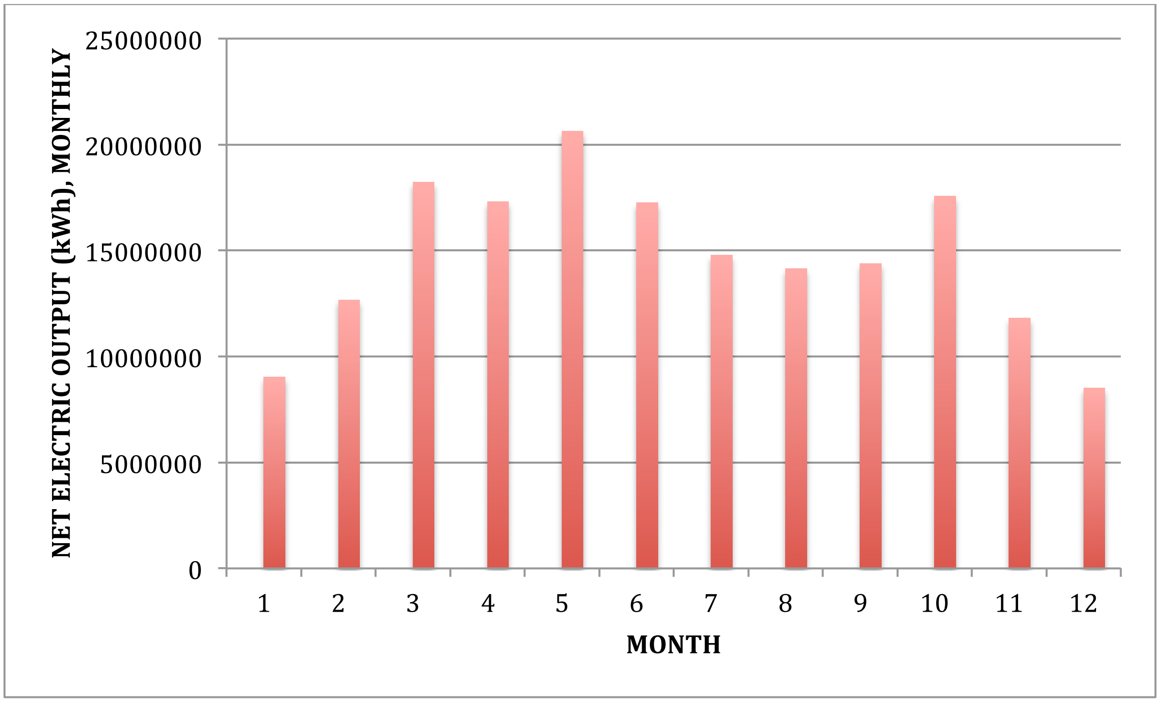

Figure 5.16 Monthly net electricity output (base case) at solar multiple 1.0

Figure 5.16 shows the monthly net electricity output (kWh) for base case, i.e., solar thermal plant equipped with evaporative cooling, operating at solar multiple value of one without hybridization and storage capacity. The size of the solar field, in conjunction with solar irradiance, determines the amount of thermal energy that will be available to the power block for electricity production. Highest monthly electricity generation of approximately 20,700 MWh is observed for the month of May indicating that highest amount of direct normal irradiation is received by the reference site (Jodhpur) during this month. Net electricity output is least for the month of December (about 8,500 MWh) due to lower DNI during this month. The input and output parameters for 100 MW base case parabolic trough system.

Table 5.5: Input and output data for 100 MW base case trough plant

Metric base	
Annual Energy	169,309,683 kWh
Capacity Factor	19.3 %
Year 1 PPA Price	37.08 ¢/kWh
LCOE Nominal	37.08 ¢/kWh
LCOE Real	31.73 ¢/kWh
Internal Rate of Return	15.00 %
Minimum DSCR	1.23
PPA Escalation	0 %
Debt Fraction	70.00%
Annual Water Usage	758,820 m^3
Total Land Area	534.94 acres

(ii) Influence of increasing solar multiple on a 100 MW solar stand alone plant without storage and hybridization

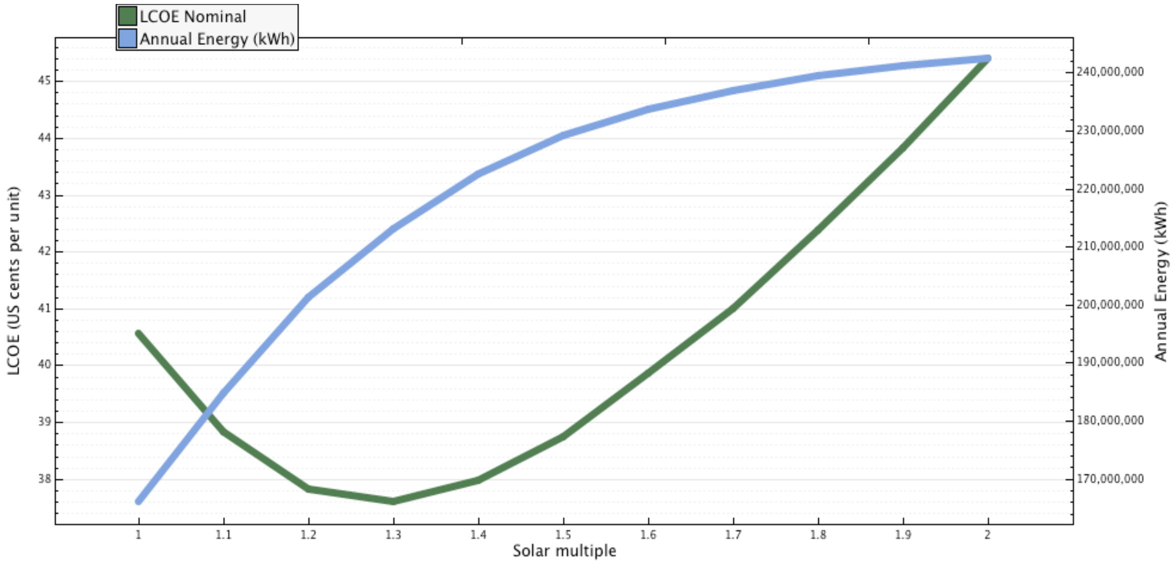

Figure 5.17 Variation in annual output and LCOE for solar stand alone plant with solar multiple values ranging from one (1) to two (2)

Figure 5.17 illustrates variation in annual energy production and LCOE of a 100 MW solar-only thermal plant as a function of solar multiple values. Parametric values for solar multiple are defined with a start value equal to one (1) and an end value to two (2) with increment of 0.1. Annual energy production denoted in Figure 5.17 increases with an increase in solar multiple value. Initially, the annual output increases steeply with increase in solar multiple value or an increase in solar field size. But more importantly, the rate of increase in energy production begins to decline at solar multiples greater than 1.3. Solar multiple of 1.3 yields about 216,600 MWh of electricity annually. Highest annual output of 242,000 MWh is observed at solar multiple of two (2).

Figure 5.17 also shows that solar multiple value of 1.3 corresponds to the lowest cost (34.4 cent/KWh) of energy generation. There is a decline in a project's economic viability on account of rising LCOE at solar multiple values less and greater than 1.3. Solar multiple value of two (2) accounts for the highest LCOE of 42.2 cent/KWh. The solar multiple value of 1.3 is indicated to be the optimal value for design of a 100 MW solar-only power plant on account of yielding lowest LCOE and a high annual energy output.

(iii) Solar trough plant integrated with fossil (natural gas) hybridization and evaporative cooling, but no storage

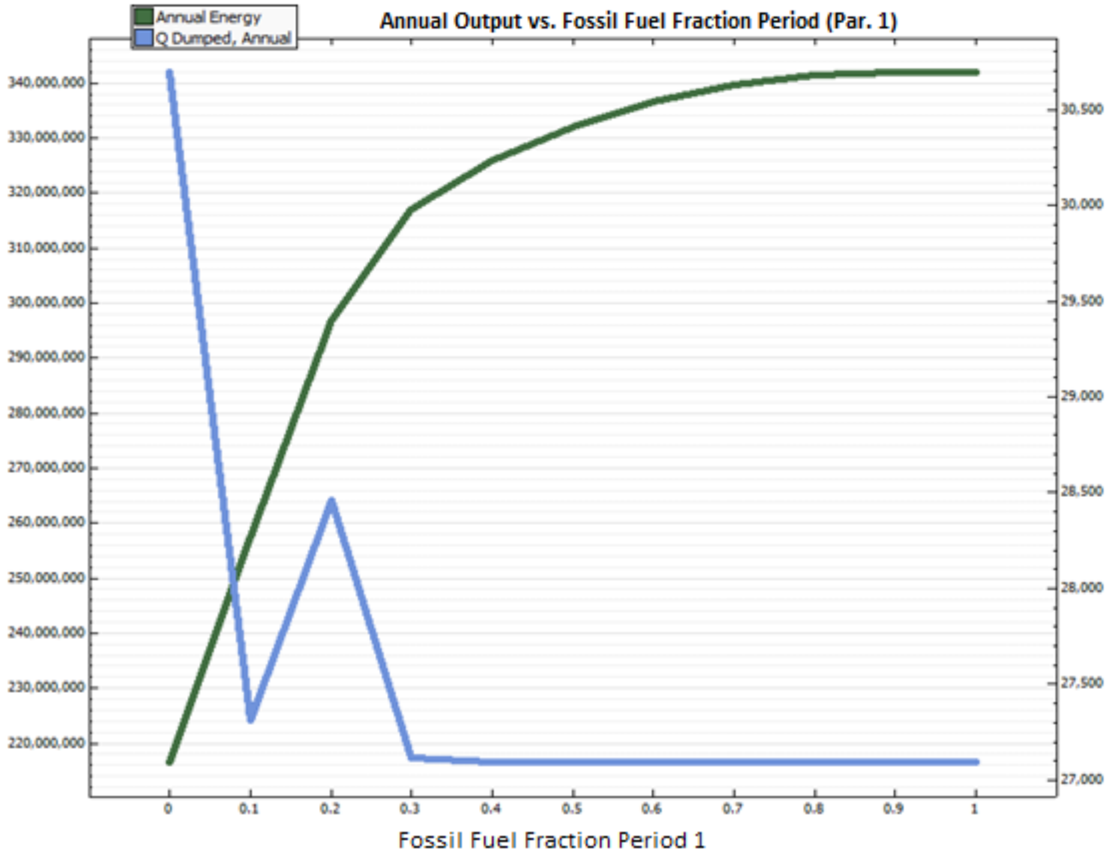

Figure 5.18 Effect of increasing fossil fuel fraction[4] on annual output and Q dumped

Figure 5.18 shows an impact of hybridization (hybrid component varied from zero to 100%) on annual energy generation and Q (energy) dumped by 100 MW solar trough with zero hours of storage LCOE decreases with increase in hybridization. However, there has to be a limit on hybridization to maintain an optimum solar content. Optimum solar content can be estimated by rate of change of annual units of electricity generation with different hybridization percentages. This study takes a 10% interval starting from zero up to 100% fossil fuel fraction in SAM which is used to run the simulations.

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[4] A fraction of the power block design turbine gross output from the Power Block page that can be met by the backup boiler. Used by the power block module to calculate the energy from the backup boiler.

Figure 5.18 also depicts the relation between amount of dumped thermal energy (Q dumped) and fossil-fuel fraction. Solar plant designed with 100% solar component i.e., nil fossil fuel fraction leads to dumping of maximum amount of thermal energy (30,700 kWh). An increase in fossil fuell fraction by 0.1 brings a sharp decline in amount of dumped thermal energy. The curve shows a slight increase at fossil fuel fraction of 0.2 and falls again at fossil fuel fraction of 0.3 (solar component of 72.2). Fossil fuell fraction of 0.3 corresponds to minimum amount of dumped thermal energy (27,150 kWh). The curve begins to flatten at fossil fuell fraction greater than 0.3 reflecting uniform waste of thermal energy. Figure 5.18 highlights the impact of increase in fossil fuell fraction on annual output of the 100 MW solar power plant. Output is least (216,000 MWh) when solar component is 100%, i.e., fossil fuel fraction is zero and maximum (342,000 MWh) when fossil fuel fraction is one (1). The output rises steeply with increase in fraction of hybrid back-up. The rate of change in output becomes uniform when fossil fuel fraction exceeds beyond 0.3. The optimal combination (solar/fossil) yielding maximum output is when fossil fuel fraction is 0.3. Table 5.6 demonstrates the influence of varying fossil fuel percentages on trough plant performance.

Table 5.6 Impact of hybridization (fossil fill) percentages on plant performance

Fossil Fill Fraction	Annual Energy Output (kWh)	Annual Fuel Usage (MWt)	Capacity Factor (%)	Q Dumped, Annual (KWh)	Thermal Energy From Solar Field (kWh)	Thermal Energy to Power Block (kWh)	Fraction of Solar component
0	21,66,05,000	1,53,996	25	27,310	72,43,15,000	84,79,87,000	100
0.1	25,74,08,000	2,51,028	29	28,463	72,36,38,000	94,90,20,000	85
0.2	29,70,68,000	2,99,747	34	27,115	72,44,88,000	1,00,23,60,000	76
0.3	31,70,25,000	3,31,110	36	27,096	72,44,67,000	1,03,23,90,000	72
0.4	32,59,13,000	3,54,378	37	27,095	72,44,27,000	1,05,46,40,000	70
0.5	33,20,25,000	3,72,589	38	27,096	72,44,07,000	1,07,20,50,000	69
0.6	33,66,03,000	3,86,017	38	27,096	72,43,96,000	1,08,48,80,000	68
0.7	33,98,03,000	3,93,509	39	27,096	72,43,94,000	1,09,20,30,000	67
0.8	34,14,18,000	3,96,284	39	27,096	72,43,94,000	1,09,46,90,000	66
0.9	34,18,69,000	3,96,730	39	27,096	72,43,94,000	1,09,51,10,000	66
1	34,19,38,000	96,730	39	27,096	72,43,94,000	1,09,51,10,000	66

(iv) Solar plant equipped with thermal storage and evaporative cooling but without hybridization

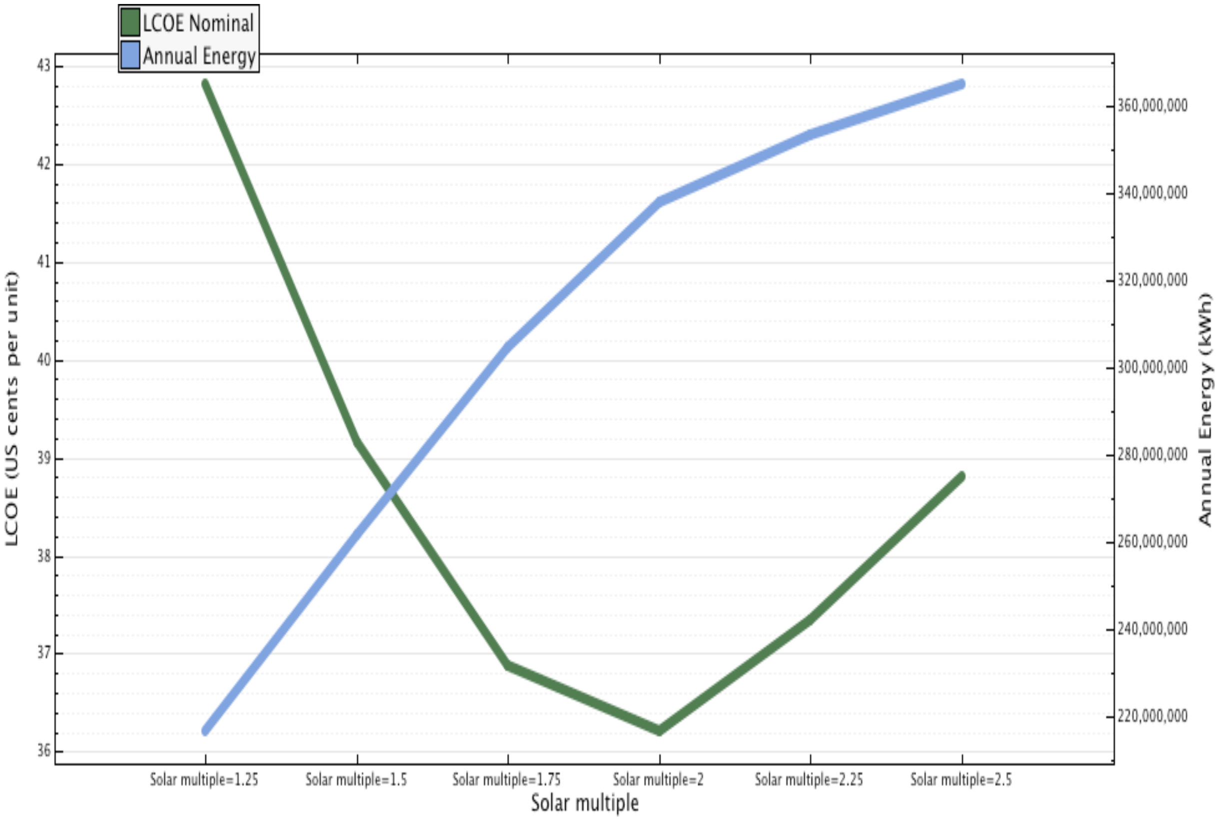

Figure 5.19 Influence of solar multiple on the LCOE and annual electricity generated by 100 MW trough plant with four hours of energy storage

The effect of solar multiple ranging from 1.25 to 2.5 is examined on a 100 MW solar trough plant coupled with four hours of storage in the present study. Most of these plants do not have a thermal storage system for maintaining the power block performance at nominal conditions during long non-insolation periods. Because of that, a proper solar field size, with respect to the electric nominal power, is a desired choice.

Figure 5.19 illustrates variation in annual output and LCOE as a function of solar multiple (ranging from 1.25 to 2.5) for a parabolic trough plant coupled with four hours of thermal energy storage. Annual electricity generated by solar power plant increases with an increase in solar field size, reaching a maximum (366,000 MWh) at solar multiple value of 2.5.

Rate of annual electricity generation witnesses a slight dip at solar multiple values greater than two. Annual output of 337,753 MWh is produced when plant operates at solar multiple of 2.0. Because of storage, power output from turbine generator remains constant through fluctuations in solar intensity in comparison to any of the solar – only configurations where rate of annual electricity production undergoes an early decline in the absence of thermal storage. Solar multiple of 2.0 can be regarded as the optimal value for trough integrated with four hours of TES. It is noticed that beyond solar multiple of 2.0, an increase in solar multiple intensity/solar field size fails to yield noticeable profit which can be a consequence of insufficient TES to shift the solar resource to periods with less sunlight.

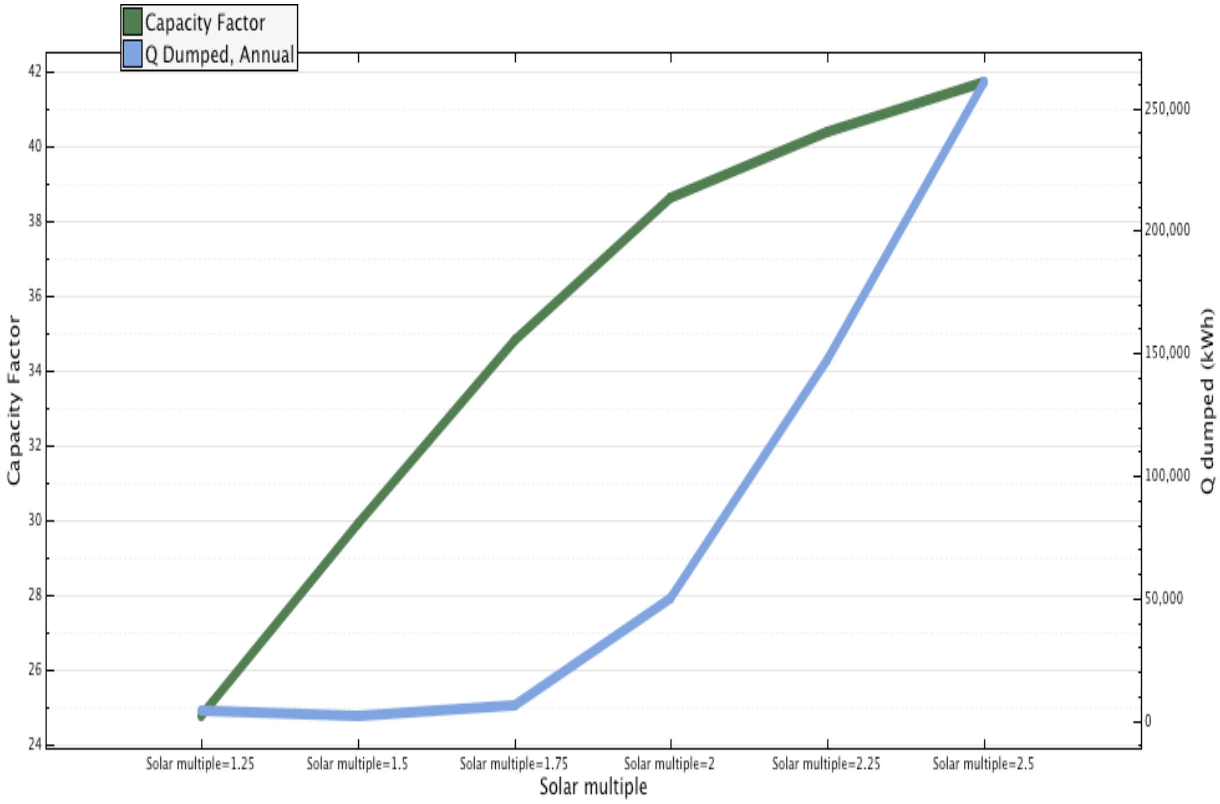

Figure 5.20 Annual capacity factors and Q dumped variation for a 100 MW trough plant with four-hour storage and solar multiple ranging from 1.25 to 2.5

Figure 5.20 shows the influence of solar multiple on the capacity factor and amount of thermal energy dumped by a 100 MW trough plant employing four hours of thermal storage. Capacity factor increases with increasing solar multiple values making use of most of the obtainable solar resource. The rate of increase in capacity factor starts to slowly decline at solar multiple values greater than 2.0. Solar multiple of 2.0 yields annual capacity factor of 36.8 %. Maximum capacity factor is observed to be approximately 41.8 % for solar multiple of 2.5. This pattern is similar to the one portrayed by annual energy versus solar multiple curve in Figure 5.20, indicating that an increase in capacity factor leads to a corresponding increase in electricity generation by a solar power plant.

Figure 5.20 also depicts varying amount of dumped thermal energy for a 100 MW trough plant with four hours of TES. Amount of thermal energy wasted by the solar power plant for solar multiples ranging from 1.25 to 1.77 is observed to be almost uniform. Figure 5.20 further shows a drastic increase at solar multiple values greater than 2.0. An oversized solar field (higher solar multiple values) results in wastage of a large amount of thermal energy because the power block will not have sufficient capacity to use the thermal energy from the solar field in many hours. Solar multiple value of 2.0 amounts to dumping of 48,000 kWh of thermal energy. Solar field size with solar multiple of 2.5 corresponds to the maximum amount of thermal energy dumped annually (260,000 kWh). Figures 5.19 and 5.20 identify solar multiple of 2.0 as the optimal value for solar trough design coupled with four-hour storage capacity.

Four different plant configurations are compared for the initial analysis. These includes two solar-only plants (differing in optimal solar multiples) without storage and hybridization, one hybrid solar plant, one solar-only plant with storage capacity ranging anywhere between 0-10 hours.

Table 5.7 Configuration and performance of 4 different 100 MW CSP trough plants

Parameter	Solar Only	Solar Only	Solar + Gas (Hybrid)	Solar + Four hour Thermal Storage
Solar Multiple	1	1.3	1.3	2
Annual electricity generation (MWh)	1,69,309	2,16,604	3,17,025	3,37,753
Solar fraction	1	1	0.72	1
Capacity Factor (%)	19.3	24.8	36.23	38.6
LCOE($ cents/kWh)	34.1	31.82	-	33.55

Table 5.7 summarizes the impact of solar field size/solar multiple value, storage and hybridization on performance of solar trough plants found in this study. Solar multiple is the ratio of solar field thermal energy to power block thermal demand at design point conditions. Higher solar multiple/solar field size yields higher annual electricity output due to more solar energy being captured by a larger solar field. Several SAM simulations have been run to estimate the optimum solar multiple and percentage of hybridization/fossil-fuel fraction. Among the solar-only designs, trough plant with a solar multiple equal to 1.3 has an optimum annual electric output of 216,604 MWh, whereas solar-only plant with solar multiple value of 1.0 manages to produce only 169,309 MWh electricity annually.

Solar trough plant integrated with thermal storage ranging anywhere between 0-10 hours and operating at solar multiple of 2.0 results in the optimum annual output (337,753 MWh). The greater solar multiple allows the plant to run at design point for a large fraction of the year, but necessitates dumping excess solar energy for much of the summer. Without energy storage, solar only plants are limited to annual capacity factors near 25%, as shown in Table 5.7. Solar trough plant equipped with four hours of thermal storage conjures a capacity factor of 38.6 %, which is almost 6.7 % higher than solar plant equipped with 28% of fossil fraction. SAM simulation has been run to estimate the optimum storage of four hours for a trough plant. It is recommended that at least one demonstration project should be based on a minimum of four hours of storage.

SAM simulation has been for zero to 100 % of hybridization with natural gas. Hybrid designs utilize shared infrastructure that reduces the capital cost compared to separate stand-alone plants. Solar/fossil hybrid designs reduce the impact of solar intermittency by providing either fossil backup to the solar plant or integrating solar output into a much larger fossil power installation. 72% solar component and 28% gas fraction is found to be the optimum configuration for a hybrid plant. It is recommended that at least one hybrid demonstration project should be based with a maximum of 30% gas fraction.

It can be observed from Table 5.7 that despite costing more for the larger solar field, solar only plant design using solar multiple of 1.3 has a slightly lower levelized cost of electricity (LCOE) of 31.82 $/kWh than the solar-only plant with solar multiple equal to 1.0 (34.10 $/kWh), suggesting a favored solar only design of the two. Integration of solar trough with thermal storage capacity results in a minor hike in LCOE of about 5.15% as shown in Table 5.7. This implies that although storage increases the cost of plant, plants equipped with high storage capacities leads to better economic utilization of the turbine which more than compensates for the increased cost due to addition of storage. Trough plant equipped with fossil backup depict the lowest LCOE of 21.81 $/kWh since hybrid designs utilize shared infrastructure that reduces the capital cost compared to separate stand-alone plants.

This section establishes that a 100 MW parabolic trough concentrating solar thermal power plant without thermal energy storage is a viable option for Jodhpur, Rajasthan if electricity can be sold at a PPA price of 34.1 US cents/kWh, which is within the range specified by the Indian government's feed-in tariff for solar energy. The system can be optimized for better financial performance by designing with solar multiple of two and at least three hours thermal energy storage. In such case, PPA price drops to about 31.4 US cents/kWh, increasing the plant's financial viability. Although thermal energy storage has been incorporated into the system, the TES system is limited today. Sensitivity analysis is done to measure the impact of solar radiation on project economics and performance. The variation in measurement and prediction of solar radiation has a direct impact on the levelized cost of electricity and capacity factor of the 100 MW parabolic trough plant. Decrease in LCOE is a consequence of the fact that profitability of CSP project lies on electricity production, which in turn is dependent on solar irradiation. It is determined from sensitivity analysis that uncertainty in DNI uncertainly has a direct influence on LCOE and capacity factor.

Chapter 6

Recommendations and Conclusion

It is clear that accurate DNI database is the dominant problem. Accuracy to within 5% is currently out of reach of satellite-derived data without additional ground readings. Due to inter-annual variability, 10-20 years of DNI data is needed for project-specific data to reach such accuracy. Although satellite-datasets cover many regions, and can help to identify good sites, most of them are biased, meaning they have significant systematic errors.

Thus, although satellite DNI maps can be used for site-selection, these need to be verified by qualified measurements at the project development stage. Since at least one year of measurements are recommended for due diligence, this can slow down development unless a suitable meteorological station is installed as soon as possible. One solution is to use multiple datasets to find a quality-weighted best estimate. This means combining well maintained, calibrated and screened ground-based measurements and qualified time-series satellite data to analyse long-term variability at proposed sites. Also important is the benchmarking of satellite-derived DNI products with sound measurements.

1. The significant impact that measurements of solar radiation and climatic conditions will have on a solar power projects has led investors and project developers to stress the importance of gathering detailed information for potential sites. Ideally, on the ground measurements should be collected over a period of 10 years. In addition, ground measurements should be compared and correlated to satellite based analyses to present a comprehensive understanding to project stakeholders. Thus measured data will also be used for improving the accuracy of satellite-based modeling of solar radiation and validation of solar resource forecasting methods.

2. CSP project developers need accurate, ‘bankable data’ of solar radiation to establish the long-term profitability of projects and to optimise design and processes. DNI data is proving hard to come by, with developers encountering differences of up to 20-50% in accuracy. A host of issues surround DNI modelling and measuring. Existing measured data, which is routinely collected by meteorological services or universities, can be difficult for developers to access and rarely bears direct relevance to the proposed project site. But obtaining accurate, site-specific measurements is by no means straightforward. Because of the difficulties associated with obtaining reliable and accurate field data, instrumented sites might not

be located at the final plant location, meaning some form of spatial extrapolation is required.

3. Without confidence and validation, data lacks bankability. As discussed in earlier sections, development of a robust solar database for India is required and has it certified, like the CWET data for wind. Comparison and judicious selection of data sources by specialists are recommended while developing a project. Assessment has to be made of the inter-annual variability of the resource, and analysis has to be provided of the historical period on which the data was based. Developers can reduce the perceived long-term solar resource risk by using robust solar resource assessment and comparing different data sources, discussing the uncertainty and selecting the data most likely to represent the long-term resource at the specific project site. The significant impact that measurements of solar radiation and climatic conditions will have on a solar power projects have led investors and project developers to stress the importance of gathering detailed information for potential sites. Ideally, on-the-ground measurement should be collected over a period of 10 years. In addition, ground measurements should be compared and correlated to satellite-based analyses to present a comprehensive understanding to project stakeholders.

4. The available solar resource data sets including the ground data from 51 MNRE/CWET met-stations still have large uncertainties that impact the assessment of PV and CSP technology opportunities in India. One of the major sources of uncertainty in satellite-derived solar data, as well as ground measurements, is the extensive amount of dust and haze that occur over India. This can have an impact on the future viability of CSP technologies in India, as well as in assessing its impact on plant operations and outputs.

5. PV can be applied throughout the country and support many niche applications, while CSP is limited to specific regions and must be applied at a utility scale, attention must be paid to storage, solar multiple, and hybridization. Two factors have contributed the most for the dominance of PV over CSP:

Market size: PV can be installed almost everywhere CSP can, but not the other way around. Current commercial CSP technology needs higher levels of irradiance (typically those of the sunbelt countries), access to water and large-scale deployments (typically more than 20 MW, compared with the few kW of a residential PV system).

This means that there are more tech companies, investors and policy makers interested in PV than in CSP.

Technological simplicity: a PV system revolves around the solar cell, while CSP is a combination of equally critical components. PV is more of a pulg and play technology, whereas the CSP industry is spread across multiple challenges e.g. optical efficiency of collectors, heat transfer fluids or turbines etc.

However, Current CSP plants can store thermal energy for up to 16 hours, which means that their production profile can match the demand profile (just like a conventional power plant). PV is not dispatchable, as a feasible commercial energy storage system does not yet exist. Dispatchability will be increasingly important when and where renewable energies achieve high penetration rates, so two things can happen: CSP becomes a commercially viable solution before a commercial PV storage system is developed, carving its own market segment; or the PV industry quickly solves the storage issue and becomes the solar technology of choice.

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