# 1
# Introduction

## 1.1 INTRODUCTION

Energy security is an important aspect to improve quality of life. Currently our daily electricity requirement is fulfilled mostly by *fossil fuels* (81% of total generation capacity). Average electricity use (2015-16) of *India* is 1,075 kWh per capita [CEA, 2017]. Due to an increase in population in *India* every year, the demand for electricity is increasing. For any developing country, the availability of sufficient electricity in industry, household, and all working sectors is important. One can also see recent changes in climate and increase in *GHG* (greenhouse gases) values. Hence to save our planet and to fulfil the energy needs, various sources of renewable energy are explored. Prior research conducted shows estimated finite and renewable sources potential [Perez and Perez, 2015].

Available energy options for electricity generation using renewables are *solar*, *wind*, *tidal*, *hydro*, *geo-thermal* and *biofuels*. Solar radiation comes out as an abundant source of energy [Cottrell *et al.*, 2015] as seen in Table 1.1. From a broader perspective, all these renewable energy options represent result of direct or indirect interactions of the solar radiation with *Earth's* climate and ground surface. Wind energy has grown impressively at a rate with 20 GW installed and a proposed target of 30 GW will be achieved by 2022 [CEA (1), 2017]. Less area, longer working power production and less maintenance (when compared with the solar plant) make the wind farm popular. Wind resource assessment at various locations has achieved a reasonable state of maturity in India. Solar resource assessment is still in its infancy. Therefore, in this chapter solar radiation potential is studied. An outline of the whole thesis is also given.

## 1.2 SOLAR RADIATION RESOURCES AND ITS DESCRIPTION

A substantial number of practical applications of solar energy have become significant in recent years. Solar photovoltaic and solar thermal power plants have undoubtedly gained large popularity in various countries. Solar applications for maintaining household comfort conditions (space cooling and heating) continue to be popular for progressively improving the energy efficiency of buildings. All solar energy applications are important for human use, but renewable power generation is the most important. As it is a high-grade energy (in the form of electricity) amenable for evacuation to the available grid and distribution infrastructure.

Solar power generation can be obtained by two routes: (i) Solar Photovoltaic (ii) Solar thermal. Solar photovoltaic (PV) cells instantly convert solar energy to electrical power (DC). These PV cells are made using semiconductor materials (sandwiched with each other) and when a photon strikes on it, current flows. Now cells are assembled together in a logical sequence and corresponding (modules, strings or arrays) layout is decided, suiting to plant capacity.

**Table 1.1** 2009 Estimate of Finite and Renewable Energy Reserves [Perez and Perez, 2015]

| *Finite Sources- Terawatt-years (Total Recoverable Reserve)* | *Renewable Sources- Terawatt-years per Yearly Potential* |
|---|---|
| Coal – 900<br>Uranium – 90-300<br>Petroleum – 240<br>Natural Gas – 215 | Solar – 23000<br>Wind – 70-120<br>OTEC – 3-11<br>Biomass – 2-6<br>Hydro – 3-4<br>Geothermal and Tides – 0.32 (Each) |

Another form of solar power generation is a concentrated system, where the incoming direct sun rays are focused at one specific point (e.g. Concentrated PV). The high concentration lenses focus sunlight on a well-ventilated PV system. These systems use less area than standard PV cells and one can reasonably achieve 2-3 times more electricity generation for same area. Solar thermal systems (Parabolic, Scheffler, etc.) use mirrors/reflectors that focus all radiation on a specific energy absorbing source (line or a point) and high concentration factors can be achieved in such cases.

Passive solar heating is one in which heat energy is stored in a confined space. It is to be used afterwards to maintain the comfort conditions of designed architecture. Therefore to conserve this energy, in the sunrise direction a "Trombe" wall [Mazria, 1979] is constructed. In the morning this stores the heat energy in small confined space and while at night, energy is released. It is also suggested that using both active and passive approaches, one can sufficiently satisfy all daily energy demands leading to the concept of zero energy buildings [José *et al.*, 2014].

Good quality solar radiation data is the main input required for solar resource assessment for the above listed applications. Therefore, for site selection of a solar power plant, one looks for properly measured and reliable solar radiation database. The solar energy coming from the sun is measured by various radiation measuring instruments. The measured values are stored at a suitable frequency in the data servers. This historical database available for a given location includes values of irradiance and luminance values. Where for recording luminance values, sky images of any selected location and the historical data captured using satellite and ground-based imaging systems are used. These datasets are derived using either terrestrial stations or satellite-derived values from sources like *NREL*, *NASA*, etc. But its spatial resolution is in km or degrees, which during analysis may lead to some uncertainty in the database. This historical long-term radiation database is available for some locations, and for calculating solar radiation data any desired location, all nearby locations ground station data are interpolated or extrapolated. Satellite databases are freely/openly available for daily or hourly average values. But for lower than sub-hourly averages one needs to purchase the historical data. Ground station provides measured values at one-minute interval. These databases are highly priced because of individual station setup. In database evaluation, for all location datasets: yearly, monthly and daily averages with their relative accuracy are compared for previous years. Also by managing all these available databases, historical data can be combined in the form of a comprehensive map. Therefore, a comprehensive "Solar map" is produced, which uses monthly and hourly averaged values. These solar maps are used for any basic site analysis [NREL(1), 2017; SolarGIS, 2017; IRENA, 2017; C-WET, 2017]. Hence, for a general site overview, satellite database is used. It is necessary have at least one year ground station radiation data to take decisions about solar power plant design.

In this thesis, the location identified for data analysis is Jodhpur, which is located in the "Hot and Dry" region (climate condition type). The radiation database available for this location is of 1-2 year duration with a measurement frequency of 1-minute to 1-hour averaged interval data. Also in this database, all three radiation components are available at uniform measurement interval. Additional meteorological parameters are also measured by this station, but they are not used in the analysis. Here climate condition can be analyzed using Köopen classification [Kottek *et al.*, 2006] and MNRE, (2006) guidelines. For Indian locations, the climatic group is classified using [MNRE, 2006]. In addition, analyzing historical information present for our selected location, knowledge of the local climatic condition is obtained. The presence of loose sand and dust present in the atmosphere, affects the radiation measurement ability of instruments. Man-made artificial cloud (because of the burning of fuel and other activities), equally affects the station's radiation potential. For a deeper understanding of climate condition, such as in climatology, the analysis may be done using various measured climatic parameters (atmospheric turbidity and various aerosol values). In this research work, this aspect is not discussed, as there is no availability of these measured values at the desired frequency (only monthly and daily average available). Only with the use of measured solar radiation database, various climatic conditions are classified.

During the analysis of the historical database, it is identified that the measuring instruments used are not as accurate as state of the art. Therefore, the historical database needs some rationalization with the present database. Also measuring instruments are of various types, which have different radiation sensing mechanisms and measuring the value at different intervals. The instruments used for radiation measurement are standardized using World Meteorological Organization (WMO) [WMO (1), 2011] & Baseline Surface Radiation Network (BSRN) [Long et al., 2002] guidelines. All these conditions are discussed in detail in the following chapters.

## 1.3 AUTHOR'S CONTRIBUTIONS

This work proposes the efficient use of various data quality checks and gap filling approaches, for estimating the real solar radiation potential of a given location. Here a "Hot and Dry" location is selected (Jodhpur, Rajasthan), as the site has high radiation potential for solar power plant installations. This site is selected because it has the most number of clear sunshine days and favorable climate conditions for the installation of the solar power plant. A correct and reliable dataset of this location is always in demand by various plant designers. This site has an old ground station established by IMD and a recent ground station established by C-WET. These databases are analyzed using application of data quality check to separate erroneous data. The measured solar radiation dataset is also compared with theoretical clear sky models. This process of proper identification and correction is important in data analysis, as it affects the solar resource assessment. Another meaningful contribution is shown in filling the identified missing gaps in the database. Various gap filling approaches are compared and overall guidelines are provided, which are simple to apply and can fill any type of gaps in solar radiation database. The results generated by this analysis are found to be beneficent in understanding the solar radiation pattern at any given site and variations in the presence of various cloud conditions. Moreover, statistical error guidelines help us in the selection of optimal techniques and approaches used in data quality check and gap filling approaches. In conclusion, to verify the authenticity of results, various gap filling algorithms are compared for radiation databases for a given location and differences are properly examined.

### 1.3.1 Problem Description

Proper analysis of measured solar radiation database is still a problem that requires extensive research. Various historical databases of different intervals and measurement approaches are available for analysis. Because of this, analyzing any ground station database and deriving conclusions from this, is challenging. Also, the measuring instruments need proper calibration and maintenance, otherwise the data measured will be unreliable. But to maintain these quality standards is not easy, and data once measured will become a standard database for that location and its modification is not suggested. Standard quality control guidelines are available in the literature, by which one can check the measured radiation data quality. But prediction of measurement error present in radiation component requires some additional tests and observations. If gaps identified are due to natural climate conditions, then they are not disturbed. But if it is due to environmental or instrumental conditions, one can try correcting it, by using various gap-filling approach guidelines. However, there are no perfect guidelines for gap filling proposed in the literature (at the sub-hourly interval), as for different locations different gap-filling approaches are found to be valid.

### 1.3.2 Proposed Work

For the selected solar radiation database (Hot and Dry region) of one year (2015, IMD-Jodhpur, 10-minute interval) complete solar radiation data analysis is proposed here. Detailed data quality check will be done using all available and relevant guidelines. Also during this analysis, various types of errors will be identified which are then correspondingly flagged. If found necessary, various gap-filling approaches provided in the literature are used. On the basis of various climatic conditions detailed analysis is undertaken on missing gap types and gap-filling approaches. Moreover, for each mentioned condition above, obtained results are discussed in each chapter. Finally, the whole database is carefully analyzed and by using all suggested guidelines, a corrected database is created. Also, in the end original site potential is compared with corrected solar potential in per day analysis, to observe the difference between them. These results have implications for various solar energy applications.

### 1.3.3 Proposed Methodology

The basic outline of the proposed work is as follows:

1. Literature survey of solar radiation measuring instruments, data quality control, cloud analysis (clear-sky and overcast sky) and gap filling approaches
2. Study of solar radiation measuring station instruments and their calibration
3. Data collection and it's pre-processing
4. Time-step analysis and maintaining uniform interval consistency
5. Identification of different climatic conditions
6. Basic and advanced data quality control approach applied to our selected database
7. Various gap filling approaches applied to different climatic conditions. Gap filling for different gap types, cloud types, and different gap approaches are analyzed
8. Comparison of raw database and modified database (after application of quality control) for estimate of a site solar potential

## 1.4 THESIS ORGANIZATION

This thesis is providing a comprehensive approach to prepare a reliable database of the selected station. Here each section will explain step by step analysis of the database, and its final objective is to make it free from all unwanted errors. The work is divided into six sections. In the first section (**Chapter 2**), brief literature reviews of all fundamentals needed are discussed. It includes solar radiation measuring instruments, radiation models, data quality control and data gap filling approaches. This chapter develops a fundamental understanding of analysis of solar radiation database and various errors. Available quality control and gap filling approaches are discussed to check and correct the measured radiation database. Different clear sky condition models are also discussed. Some statistical indicators are discussed, so that results derived after final analysis and available raw database can be compared.

Next section (**Chapter 3**) discusses radiation instruments, used in solar radiation measurement and their possible responses at different error conditions. Using these selected locations' climatic condition is described and its direct influence on solar radiation falling at that location is examined. Unique responses of the instrument are examined and their influence on other instruments are also discussed here. From the available database, some typical days are selected, which helps in the proper identification of various cloud condition days.

The third section (**Chapter 4**) includes discussion of solar radiation data quality control guidelines. All possible tests used in the determination of various errors from measured radiation databases are discussed here. Some additional (optional) tests are also provided, which can be used for location specific error identification. Now for a better understanding of various discussed measurement errors, some sample days are identified and related quality control plots are made. Information related to climate and instrumental errors are compiled here. As in normal days, the presence of all types of errors is possible.

The fourth section (**Chapter 5**) includes various gap filling approaches used in solar radiation measurement. Specific days of interest are selected from location database and measurement quality is identified using previous chapter guidelines. Now corrected database is finally processed and artificial gaps are introduced in it. Using various gap filling approaches, these missing gaps are filled. All produced results are compared using RMSE values, and possible conclusions are discussed on the basis of different gaps present and various climate conditions.

The fifth section (**Chapter 6**) relates all knowledge gained in previous sections. The radiation database for the year 2015, IMD-Jodhpur, 10-minute averaged radiation database is carefully corrected. A comparison is made between both raw and modified database and end results are analysed on the basis of daily averaged values. The approach providing low RMSE value is selected and accordingly corrected radiation potential can be calculated. Further other available database is also compared by calculating monthly and yearly averaged values.

Finally, the sixth section **(Chapter 7)** summarizes and concludes the work and discusses future research possibilities.

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