Highlights

- Performance evaluation of solar photovoltaic projects under India's Solar Mission
- Inter-comparability of solar radiation databases for solar photovoltaic projects
- Mean percentage error analysis for capacity factor and levelized cost of electricity
- Energy yield assessment of photovoltaic projects using solar radiation databases
- Long-term measured or high-resolution time series databases should be preferred

Performance assessment of grid-interactive solar photovoltaic projects under India's national solar mission

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Abstract

Lack of long-term global solar radiation data has often been a significant challenge to the solar power sector development primarily in developing countries. The choice of a solar radiation database is projected to have a considerable impact on the predicted performance of a solar power project and consequently on its techno-commercial viability. Therefore, use of reliable and well- characterized solar radiation data source is important for bankability of solar power projects. This study presents the technical and economic performance evaluation of grid-interactive solar photovoltaic (PV) projects implemented under the first phase of India's national solar mission. For performance assessment, we compare annual energy yield predictions using several solar radiation databases and monitored data of 39 solar PV power plants located across the country. Technical simulations have been carried out for each project location using static and dynamic solar irradiance data obtained from various databases available in the Indian context. PV_{SYST} model has been used for energy yield assessment of solar PV projects after taking into account the key design and technical parameters and associated energy losses during solar energy conversion. The inter-comparability of capacity utilization factor and levelized cost of electricity of operational solar PV projects have also been analyzed with the estimates obtained through different solar radiation databases. Mutual deviation for the techno-economic performance of solar PV projects varied from -12% to 31% for the projects under the first phase of India's solar mission. Our study indicates that the long-term measured or high-resolution time series databases should be preferred for the bankability of solar power projects. Further, solar power policies of the country must provide clear guidelines for selection of solar radiation databases to enhance their bankability.

***Key words*:** Solar photovoltaic, National solar mission, Global horizontal irradiance, Solar radiation databases, Capacity utilization factor, Levelized cost of electricity

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Nomenclature

AC	:	Alternating Current
CdTe	:	Cadmium Telluride
CERC	:	Central Electricity Regulatory Commission
COD	:	Commercial Operation Date
CSP	:	Concentrating Solar Power
CUF	:	Capacity Utilization Factor
DC	:	Direct Current
EPC	:	Engineering, Procurement and Commissioning
FiT	:	Feed-in Tariff
EYA	:	Energy Yield Assessment
GBI	:	Generation Based Incentive
GHI	:	Global Horizontal Irradiance
GSS	:	Grid Sub Station
IEA	:	International Energy Agency
IMD	:	Indian Meteorological Department
IREDA	:	Indian Renewable Energy Development Agency
JNNSM	:	Jawaharlal Nehru National Solar Mission
kW	:	Kilowatts
kWp	:	Kilowatt Peak
LCOE	:	Levelized Cost of Electricity
MC	:	Multi-Crystalline
MNRE	:	Ministry of New and Renewable Energy
MPE	:	Mean Percentage Error
MW	:	Megawatts
MWp	:	Megawatt Peak
NASA	:	National Aeronautics and Space Administration
NEG	:	Net energy Generation
NIWE	:	National Institute of Wind Energy
NREL	:	National Renewable Energy Laboratory
NSM	:	National Solar Mission
NTPC	:	National Thermal Power Corporation
NVVN	:	NTPC Vidyut Vitran Nigam
O&M	:	Operational and Maintenance
OPEX	:	Operation and Maintenance Cost
PPA	:	Power Purchase Agreement
PR	:	Performance Ratio
PV	:	Photovoltaic
PVPS	:	Photovoltaic Power Systems Programme
RE	:	Renewable Energy
REMS	:	Renewable Energy Management Stations
RPSSGP	:	Rooftop Solar PV and Small Solar Power Generation Programme
SECI	:	Solar Energy Corporation of India
SEG		Specific Energy Generation
SLDC	:	State Load Dispatch Center

SPP	:	Solar Power Project
SRDB	:	Solar Radiation Database
SWERA	:	Solar and Wind Energy Resource Assessment
TF	:	Thin Films
TMY	:	Typical Meteorological Year
UNEP	:	United Nation Environment Programme
VGF	:	Viability Gap Funding

1. Introduction

Solar energy is one of the most promising renewable energy resources because of its widespread availability. Technology advances have drastically reduced the costs of solar PV panels by almost 80% from 2008 to 2015 [1]. In 2016, the annual installed capacity of solar PV increased approximately 50% to at least 75 GW – raising the global total installed capacity to 303 GW [2]. This rapid development of solar power projects over the world requires substantial investments, financial/economic risk assessment and stable policy framework about which solar technology should be installed in priority in a given location [3-5]. A major concern of the SPP stakeholders (including project developers, EPC and O&M contractors, financier, etc.) is that how much solar electricity can be generated by any SPP in a given location. This is especially true for 126 countries worldwide with feed-in tariff policies [2]: due to fixed tariffs and guaranteed rights to feed in all electricity generated [6], one of the major uncertainties for an investment in an SPP is the evaluation of the expected electricity generation within its lifetime or its investment time horizon [7-8].

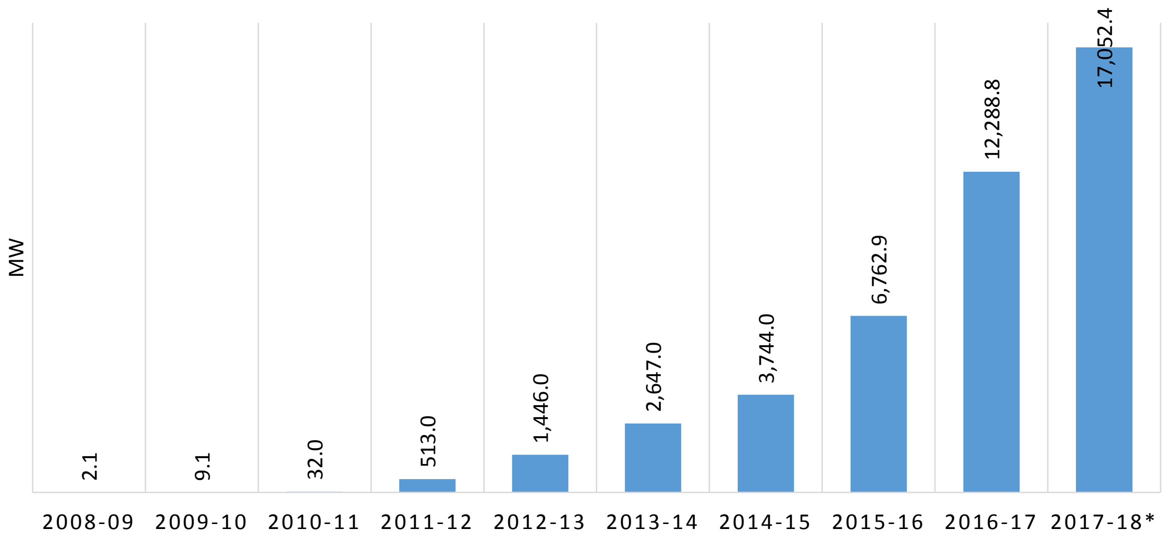
The availability of solar radiation data for a given location under consideration is essential for performance assessment of PV projects. The performance of PV systems in terms of predicted annual yield[2] would depend upon the availability of global horizontal irradiance as provided in the solar radiation database used besides several other designs and operational variables [9-10]. Solar-resource uncertainty and inherent seasonal variability represent a performance and revenue risk for an SPP that is tied primarily to the quality of the data (i.e. GHI) available and the commercial risks dictated by the contractual arrangements governing the sale of solar electricity [11]. Therefore, the choice of an SRDB is expected to have a considerable impact on the predicted performance of an SPP and consequently on its techno-commercial feasibility [12]. For example, use of an SRDB that provides higher GHI values (as compared to those actually available through the ground measurements) would overestimate the annual energy yield. Consequently, the actual field performance of a PV system would not match the performance predicted using the SRDB. In such a situation, the stakeholders may incur a substantial financial loss as the viability of the PV system was appraised based on higher GHI values. Therefore, for the economic viability of a PV project, the choice of the SRDB is critically important.

India, being a tropical country, is endowed with vast solar energy potential where most parts of the country receive 4-7 kWh/m^2/day of solar radiation [13] with 250-300 sunny days in a year [14]. In 2010, the Indian government launched the National Solar Mission (also known as the JNNSM) under its National Action Plan on Climate Change with a target of (i) deployment of 20 GW of grid-connected solar power by 2022, (ii) 2 GW of off-grid solar applications including 20 million solar lights by 2022, and (iii) 20 million m^2 solar thermal collector area [15]. In its Intended Nationally Determined

[2] Annual yield prediction is an estimate of the annual electricity generation by a PV system at a specific location.

Contributions under the Paris Agreement, India committed to increasing the amount of electric power from non-fossil resources to 40% by 2030 [16]. A total of 175 GW of RE installed capacity was promised to be achieved by 2022, of which 100 GW is the target set for solar power alone, 60 GW of wind power, 10 GW of biomass and 5 GW of hydro projects by 2022 [15]. The upgraded target of 100 GW from solar is planned to be achieved in seven years period and approximately consist of 40 GW grid-interactive rooftop projects and 60 GW large and medium size ground-mounted SPPs [15-17]. Appropriately designed transmission infrastructure and updated grid integration and operation mechanisms are key to scaling-up RE to 175 GW by 2022 [18]. Internationally, where penetration of RE has been increasing in the power generation mix, various changes to grid design, technology, and its operation have been implemented to allow cost-effective grid integration of RE [19-22]. In order to manage such a high share of intermittent power on the grid, the Indian government is working on strengthening of T&D infrastructure through developing green corridors, establishing renewable energy management stations and enhancing the capabilities of regional load dispatch centers. [23-26].

In 2008, the cumulative installed capacity of grid-connected solar power was 2.1 MW that has grown up to 17,052 MW by December 2017 [27]. Figure 1 presents the cumulative installed capacity of SPPs in India. In 2016, the newly installed capacity of PV power projects reached 3.0 GW [28]. In spite of this impressive progress, the cumulative installed capacity of SPPs is still far away from their respective potential [28-30] as in 2016 PV accounted for only 1% of electricity generation in the country [31]. Several studies have pointed out many barriers acting as a hindrance to achieving the target set by NSM [6, 32-35]. Over the years the Central/State governments and regulatory bodies have taken many paths breaking initiatives to address the impediments to the NSM. Still, there are several barriers to be overcome to achieve the revised NSM target of 100 GW by 2022.



**Installed capacity until December 2017*

Figure 1: Cumulative installed capacity of solar power projects in India

As mentioned above, the financial returns of an SPP are highly sensitive to the solar radiation levels [36] therefore, errors in the solar radiation measurements can significantly impact upon the return on investment. For the financial/economic feasibility of SPPs, a bankable solar radiation database is critically important [37-39]. The lack of long-term measured solar radiation data is one of the key barriers towards rapid implementation of SPPs in India [32, 40-42] and other developing countries [43-44]. The project developers are facing lots of problem towards financial closure and bankability of the projects due to unavailability of long-term measured data of solar radiation and other climatic parameters in India [45]. Therefore, the investors and SPP developers relay primarily on satellite and interpolated data sources of static or dynamic nature. Wang et al. [46] observed that depending upon the resolution and statistical approach different SRDBs presents different variability over different locations. Owing to the deviation in the solar irradiance a large uncertainty is observed in the overall techno-commercial viability of the SPPs [42].

For the performance assessment of PV projects, IEA's photovoltaic power systems programme analyzed 260 PV systems (grid-connected, stand-alone and hybrid systems) installed in various countries of the world [47]. The PVPS Task 2 provided suitable information on the operational performance, reliability, and costs of PV systems to various stakeholders. In addition, over the previous years, several groups of researchers conducted a performance evaluation of small and utility-scale PV projects [47-66]. The performance of PV projects are essentially analyzed in terms of a) capacity utilization factor, b) specific energy generation, c) performance ratio, d) efficiency of the PV system, and e) levelized cost of electricity. For example, PR for grid-connected PV systems is estimated at 0.6 to 0.8 from the performance analysis of 170 grid-connected PV plants in the IEA-PVPS Task 2 database [47]. Table 1 presents PR and other select performance indicators for PV projects at different locations globally. Most of the studies available in the public domain are primarily focused on technical and/or techno-economic performance assessment of PV projects and limited to either one specific project or any specific feature of a reference project. So far, performance assessment of multiple utility-scale PV projects taking into account the different solar radiation databases is limited in the public domain [42].

For bankability of large-scale SPPs, use of reliable and accurate SRDB is critically important. The choice of an SRDB is expected to have a significant impact on the predicted performance of a PV project and consequently on its technical and financial feasibility [12]. So far, there are no specific criteria defined under the NSM or Central/State solar power policies for selection of specific SRDBs. Therefore, the performance evaluation of the operational SPPs is important from the viewpoint of project developers and lenders exploring to invest in new projects in the similar vicinity of the states, EPC and O&M contractors for offering realistic warrantees and guarantees of plant performance. Obviously, greater accuracies of solar power plant performance predictions also mean less risk to investors [6]. Therefore, a preliminary attempt towards the performance evaluation and inter-comparability of large-scale (grid-interactive) PV projects in India operational under NSM Phase-I has been made in this study using actual plant performance data obtained from operational PV projects and anticipated performance using several SRDBs (i.e. ground, satellite and statistical) available in the Indian context. To test the validity of various sources of data, we have collected output measurements (viz. capacity factor, levelized cost of electricity) from 39 solar PV power plants installed under NSM Phase-I in India, which have been in operation for at least a period of 3 years. This output is used to analyze the variability of different SRDBs. Since several sources of solar radiation data are available in the Indian context, this will be useful in evaluating which source of data is the most accurate.

Table 1. Performance indicator of solar PV projects

Location	Capacity	CUF (%)	SEG (kWh/kWp)	PR	Reference
Global	Large-scale (MWp)		400-950 in Germany; 1600 in Israel; 400-1400 in Switzerland	0.6-0.8*	[47]
	0.45 to 1.5 kWp			0.10-0.60** 0.30-0.60+	
Warsaw, Poland	1 kWp		830	0.60-0.80	[48]
Mae Hong Son province, Thailand	500 kWp		767	0.70-0.90	[49]
Nordern Ireland	13 KWp			0.60-0.62	[50]
Island of Crete, Greece	171.36 kWp			0.67	[51]
Ireland	1.72 kWp	10.10		0.82	[52]
Nis, Republic of Serbia	2 kWp	12.88		0.94	[53]
Karnataka, India	3 MWp		1372	0.70	[54]
Punjab, India	190 kWp	9.27		0.74	[55]
Algeria	9.54 kWp		1151	0.62-0.77	[56]
Kerman, Iran	5.52 kWp	23.20		0.81	[57]
Al-Ahliyya Amman University, Jordan	276 kWp	18.70	1639	0.88	[58]
Ramagundam, India	10 MWp	17.68	1580	0.86	[59]
Niš (Republic of Serbia)	2 kWp	12.88		0.94	[60]
South Africa	3.2 kWp			0.84	[61]
Sivagangai (Tamilnadu), India	5 MWp		1699	0.89	[62]
Mauritania	15 MWp	17.75		0.68	[63]
Bangalore, India	20 kWp	16.50	1445	0.85	[64]
Wellington, New Zealand	10 kWp			0.78	[65]
Sai Kung, Hong Kong	19.8 kWp			0.60++	[66]

**Average of 170 grid-connected PV systems; **Average of stand-alone (without back-up); +Average of stand-alone (with back-up); ++ Stand-alone system*

The paper is set out as follows. Section 2 provides a brief overview of NSM. Section 3 presents the methodology used for performance evaluation of selected PV projects. Section 4 presents an assessment of GHI over the select PV project locations using the static and dynamic SRDBs. The impact of the variation due to solar radiation estimated by select SRDBs on the capacity factor and levelized cost of electricity delivered by the PV projects is analyzed in Section 5. Section 6 presents the mean absolute percentage error analysis of PV projects and finally, we draw conclusions in Section 7.

2. National Solar Mission of India

Large-scale solar power development in India is primarily driven by the NSM and several State-level schemes also provide strong support to solar deployment and development of solar power capacity. India's solar mission is being implemented in three phases:

2.1 NSM Phase-I

The first phase (Phase-I) of India's NSM comprised the period from 2010 to 2013 and targeted 1000 MW installed capacity for creating an initial market for solar power by bringing investors, EPC and O&M contractors and manufacturers together. In NSM Phase-I, solar PV and thermal projects were allocated in equal proportion (50:50). NSM Phase-I was commissioned in Batch-I and Batch-II, in which SPPs were allotted through a process of reverse bidding. In Batch-I, bids for 150 MW PV and 470 MW CSP were invited in August 2010 and bids for Batch-II of 350 MW PV were invited in August 2011. In Batch-I, the eligible project capacities were 5 MW for PV and up to 100 MW for CSP. 30 PV projects with an aggregate capacity of 150 MW and 7 CSP projects with an aggregate capacity of 470 MW were selected. The bid tariffs for PV projects were in the range of INR 10.95-12.76/kWh and tariffs for CSP projects were in the range of INR 10.49-12.24/kWh [68]. 26 PV projects of 140 MW and 3 CSP projects of 200 MW have been commissioned under Phase-I (Batch-I). For PV, the project capacity fixed was 5-20 MW in Batch-II. 28 PV projects with an aggregate capacity of 350 MW were selected. The tariff for the PV projects varied from INR 7.49-9.44/kWh in Batch-II. 26 PV projects of aggregate 330 MW capacity have been commissioned under Batch-II [68]. A 5 MW PV project by Delhi Mumbai Industrial Corridor Development Corporation Ltd has also been set up under the bundling scheme of NSM Phase-I. Thus, under Phase-I, 523 MW PV projects and 202.5 MW CSP projects have been commissioned under the bundling scheme.

Migration Scheme: With a view to facilitating quick start-up to NSM and also the rapid implementation of the on-going projects under advanced stage of implementation in different States, this scheme was introduced in February 2010 to allow the migration of such projects to NSM. A total of 16 projects of 84 MW capacity (13 PV projects of 54 MW and 3 CSP projects of 30 MW capacity) were approved under this scheme for long-term procurement of power by NVVN at CERC notified tariff for 2010-11 viz. INR 17.91/kWh for PV and INR 15.31/kWh for CSP [69]. 11 PV projects of 48 MW capacity and one CSP project of 2.5 MW capacity have been commissioned under this scheme.

Rooftop Solar PV and Small Solar Power Generation Programme: In June 2010, the Indian Ministry of New and Renewable Energy announced the RPSSGP guidelines for SPPs connected to distribution network below 33 kV. A key objective of RPSSGP was to encourage the States to declare their Solar

Power Policy for grid-connected projects focusing on the distribution network and to strengthen the tail-end of the grid. The role of the MNRE was to provide a fixed GBI to the State utilities at a rate equal to the difference of the CERC tariff for 2010-11 (INR 17.91/kWh) and a reference rate of INR 5.5/ kWh. The projects were registered with IREDA through a web-based process. 78 projects were selected to set up 98 MW capacity projects in 12 States. Against this, 71 projects of total capacity 90.8 MW have been connected to the grid [15].

NSM Phase-I also mandated domestic content requirement to protect domestic manufacturing. According to this policy, developers had to buy locally manufactured PVs made by crystalline silicon technology, but it was not applied in TF technology due to lack of enough manufacturers. This policy is argued among experts as being ineffective since it directed developers toward cheaper TF imported from the US and China [70-73].

2.2 NSM Phase-II

NSM Phase-II started in 2013 and will continue till 2017, with an aim to facilitate a substantial increase in on-grid solar installed capacity. PV gained higher attention (70% of the target) as compared to CSP in NSM Phase-II as CSP was not supported by developers during the Phase-I. The State Governments also became responsible for 60% total installed capacity in Phase-II. MNRE has announced three draft schemes for the second phase. In Batch I, the scheme aims for 750 MW on-grid solar with VGF in a competitive reverse bidding process for SPP developers (no FiT). In addition to VGF, the Solar Energy Corporation of India (SECI) also guaranteed to buy the generated electricity from providers at a fixed rate and also to sell it to distributors for fixed rates over the long-term. For Batch II, the MNRE has proposed a State-specific bundling scheme for the development of 3000 MW SPPs, performed by NVVN. A State-specific VGF scheme for the development of 2000 MW SPPs with PPA for 25 years operated by SECI was proposed under Phase-II [71].

In order to enhance the execution of the projects and furnish comfort to project developers towards land acquisition and infrastructure development MNRE has launched the scheme of Solar Parks (capacity 500 MW and above) [74]. At present, 34 solar parks of 20,000 MW capacity are under the different stage of development in 22 states. The competitive bidding for 750 MW Rewa Ultra Mega Solar Park in Madhya Pradesh with assistance from International Finance Corporation has reduced the tariff of solar power at INR 3.30/kWh [38]. In May 2017, solar power tariffs in India have plunged to a new low of INR 2.44 /kWh (≈3.8 US¢) for 500 MW SPP in Rajasthan [75].

3. Methodology

In this study, we have analyzed the performance of large-scale (grid-connected) PV projects in India operational from last 3-4 years from allocation through Batch-I&II of NSM Phase-I. The energy generation pattern of last 3-4 years of 39 operational PV projects of NSM Phase-I (with capacity varying from 2 to 20 MW) has been considered for performance assessment [76-78]. EYA has been carried out using PV_{SYST} computer software taking into account the key design and technical parameters and energy losses of all projects along with technology used. The simulations have been carried out for each project location using static (NASA, NREL, SWERA) and dynamic (Meteonorm, SolarGIS) solar irradiance data from various databases available in the Indian context. A detailed description of solar radiation databases is presented in Purohit and Purohit [42]. The inter-comparability of actual electricity generation through different databases has also been analyzed in the study.

To evaluate the performance and inter-comparability we have developed a 10-steps approach presented through a flow-chart diagram in Figure 2. The key steps comprise:

[1]. To collect the geographical data of the locations of the operational projects implemented in NSM Phase-I (i.e. batch-I, batch-II and projects under IREDA and migration scheme), since most of the satellite SRDBs requires latitude and longitude of the reference location as an input to generate the data.

[2]. To build up technical information about select PV projects (i.e. installed capacity, PV module technology, inverters along with their minimum functional technical specifications etc.).

[3]. To collect the design aspects of the projects which comprise the technical specification of PV modules, inverters and tracking systems (if used). This step will specify the module break-up (with respect to ratings) and the design consideration (tilt, seasonal adjustment, tracking etc.)

[4]. To accrue operational information of the project that mainly comprises the voltage level at which power evacuation is carried out, grid substation and information about the metering point.

[5]. To collect data on actual electricity generation through PV projects from their commercial operation date. For inter-comparability, representation of the actual electricity generation for a complete year is used.

[6]. To generate solar irradiance and meteorological data over the locations of select projects using ground, satellite and time series databases. All static and dynamic data is converted into TMY format for time series assessment of PV projects.

[7]. To assess energy yield of PV projects using PV_{SYST} (along with select solar and meteorological databases) taking into account the associated actual design/technological features. The simulation exercise comprises the optimization of respective technical losses (DC/AC).

[8]. To develop a financial model to estimate the LCOE after taking into account the benchmarking cost for PV projects from CERC [69]. The model takes into account the key financial considerations as per the best industrial practice in Indian PV market.

[9]. To evaluate the inter-comparability of the technical (CUF) and economic (LCOE) parameters obtained through simulations under various solar and meteorological databases with respect to the energy generation by the respective PV projects.

[10]. To analyze the simulated and actual plant performance data and statistical assessment through MPE associated with technical and financial indicators.

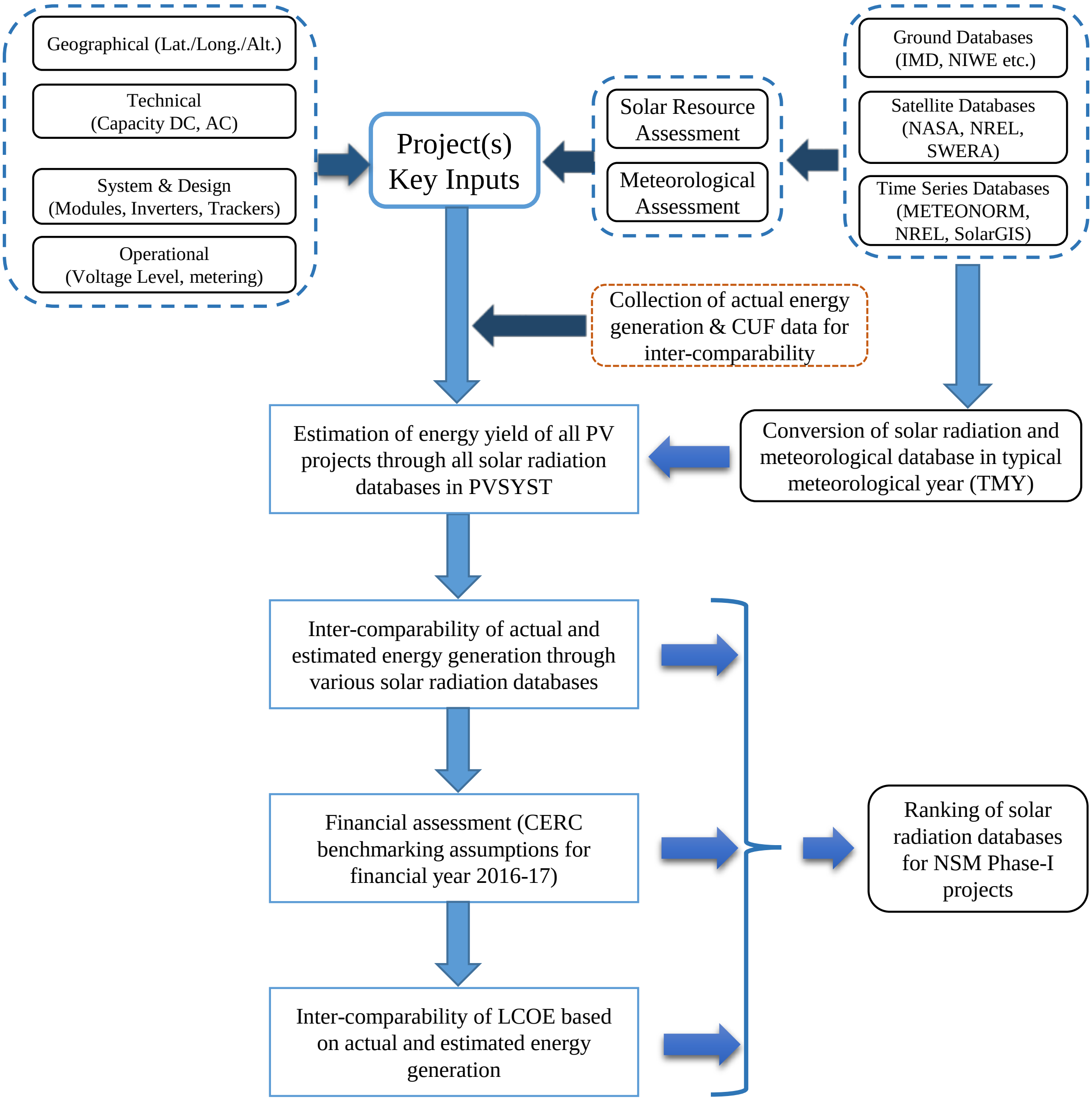


Figure 2: Flow chart of the methodology used for the performance evaluation of PV projects

It has been observed that under NSM Phase-I, the concentration of SPPs was mainly focused on the state of Rajasthan; however few projects have been implemented in the states of Andhra Pradesh, Tamil Nadu, Odisha, and Maharashtra. We select 39 PV projects from NSM Phase-I for which complete technical, design and performance details were available. Table A.1 presents the technical details of the PV projects under NSM Phase-I (see: Appendix-I). 30 projects from Batch I&II (15 from each) have been selected (Table A.1). Under Batch-I, the maximum project capacity was 5 MW; however, under Batch-II, it has been increased up to 20 MW. The capacity of migration projects was 5 MW; however, IREDA projects were limited up to 2 MW capacity. Further, 4 projects from migration scheme and 5 projects from IREDA have been selected for performance evaluation.

4. Evaluation of Global Horizontal Irradiance over the Solar PV Project Locations

Accuracy in the prediction of GHI is critically important for PV performance, its installation and pre-sizing studies. Any change in the solar radiation directly impacts the electricity generation and in turn, the economics of the SPPs. There are several GHI databases available in the Indian context which may be categorized into two broad categories namely - *Static* and *Dynamic*. The *Static* databases are essentially ground (measured) and low-resolution databases that present long-term and short-term solar radiation values in monthly average daily formats. However, the *Dynamic* databases are high-resolution satellite and/or interpolated databases that comprise hourly values of GHI of a number of years continuously. Bankability is the key limitation of *Static* databases as the range and bandwidth of uncertainty of data is not standardized. The key features of the select SRDBs used in the performance assessment of PV projects have been explained in Purohit and Purohit [42] and briefly summarized in Table A.2 of Appendix-I. Figure 3 presents the classification of SRDBs in the Indian context.

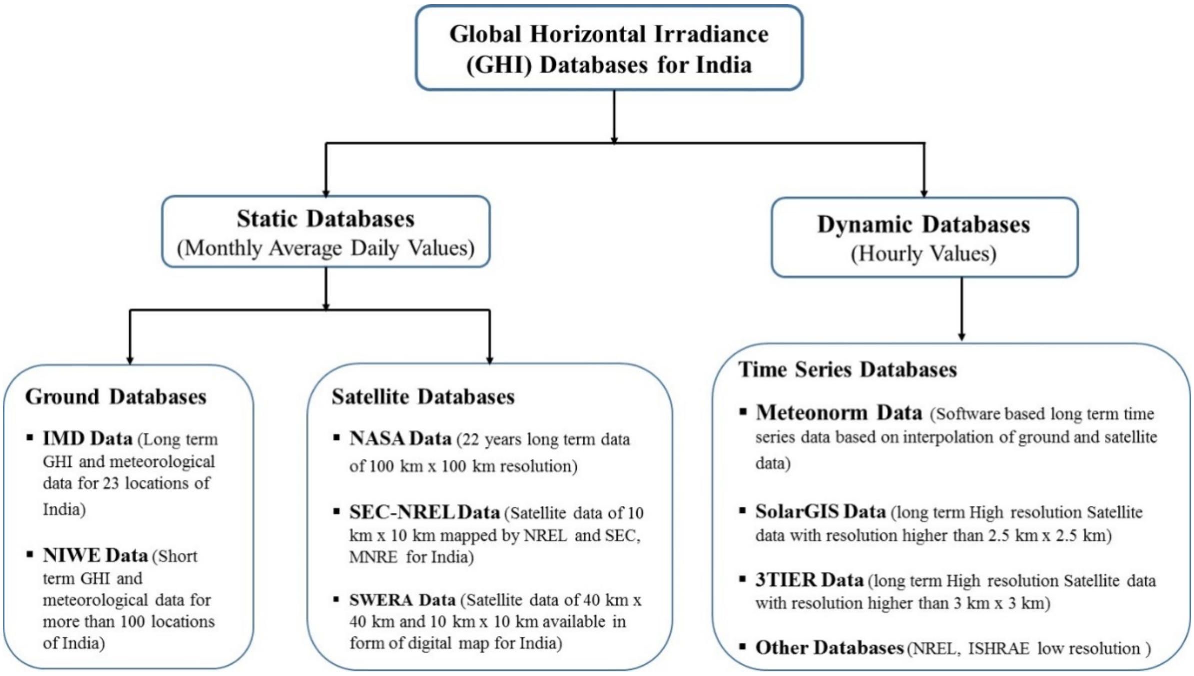


Figure 3: Solar radiation databases available in the Indian context

For performance evaluation of PV projects, the above-mentioned weather databases (except 3TIER) were converted into a uniform code that is acceptable to PV_{SYST} for evaluating electricity output of PV projects. In order to convert static (monthly average daily) GHI data in TMY format the following mathematical expression developed by Collares-Pereira and Rabl [79] has been used.

$$r_t = \frac{\pi}{24}\,(a + b\,cos\omega)\,\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\,\omega_s}{180}\cos\omega_s} \tag{1}$$

where r_t is the ratio of hourly total to daily total radiation as a function of the daily length and hour, ω represents the hour angle in degrees and ω_s the sunset hour angle. The coefficient *a* and *b* are given by;

$$a = 0.409 + 0.5016 (\sin \omega_s - 60) \tag{2}$$

$$b = 0.6609 + 0.4767 (\sin \omega_s - 60) \tag{3}$$

In order to estimate global solar irradiance over any inclined or tracking surface the information of diffuse irradiance is essential. PV_{SYST} takes GHI as an input and gives the hourly values of diffuse irradiance using the inbuilt empirical model developed by Liu and Jorden [80] and converted into hourly format as following;

$$r_d = \frac{\pi}{24} \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \frac{\pi \omega_s}{180} \cos \omega_s} \tag{4}$$

where r_d represents the ratio of hourly diffuse to daily diffuse radiation.

Using the hourly values of GHI and diffuse irradiance, the PV_{SYST} can estimate the solar irradiance over any inclined surface using mathematical formulations. Further using hourly values of solar irradiance and meteorological parameters (ambient temperature, relative humidity, wind speed etc.) the data files have been converted to TMY format. The annual GHI obtained through above-mentioned SRDBs over the select project locations are presented in Table S.1 of the supplementary section. Apart from solar irradiance, meteorological parameters (viz. ambient temperature, relative humidity, prevailing wind, and precipitation etc.) also affect the performance of PV projects directly or indirectly. In this exercise, while we developed TMY files for project locations the meteorological parameters have also been taken into account from respective databases.

It has been observed that under NSM Phase-I, all select locations receive annual GHI >1800 kWh/m^2 through all SRDBs. The key issue with the ground data collected in this exercise is the IMD long-term data that is not relevant with respect to the select project location as it is located very far from the weather station location. However, NIWE weather station is closer to project location but data availability is for 1-2 years (short-term) only. Therefore, the EYA for the point of view of techno-economic inter-comparability has not been carried out with ground databases in this study.

5. Energy Yield Assessment of Solar PV Projects

EYA has been carried out for all PV projects considered in this study with the above-mentioned solar radiation and meteorological databases by using PV_{SYST}[3] (version 6.5) after taking into account the geographical and project-specific design parameters. The respective product data files (*.PAN) for PV modules and inverters (*.OND) have been accessed from PV_{SYST} product gallery.

[3]PV_{SYST} 6.5 is a PC software package for the study, sizing, simulation and data analysis of complete PV systems. It is suitable for grid-connected, stand-alone, pumping and DC-grid systems, and offers an extensive meteorological and PV-components database.

5.1 Actual energy generation

In this study, actual energy generation data of the operational PV projects have been taken from their commercial operation date. The month-wise CUF for a complete year has been presented in Table S.2 of the supplementary section, taken as the reference case for inter-comparability. As there are projects operational from more than three years the energy generation data of the recent year has been considered in order to minimize the deviation due to plant stabilization after commissioning, initial year degradation etc. It has been observed that under NSM Phase-I most of the projects have achieved annual CUF ≥18% except 5 MW project of Essel MP Energy Ltd (14.42%) under Batch-II and 3 projects under IREDA scheme. Out of 15 select projects under NSM Phase-I (Batch-I), all projects reported annual CUF ≥18% (two projects reported CUF ≥22%, 5 projects reported CUF≥21%, 10 projects reported CUF≥20%, and 12 projects reported CUF≥19%) which established a positive performance framework for PV market in the country. The average CUF for all NSM Phase-I (Batch-I) has been achieved at 20.33% that is higher than its benchmarked value of 19% by CERC [69].

On the ground, the performance of the PV projects under Batch-II has been experienced more attractive as compared to Batch-I projects. The bandwidth of project capacity for Batch-II varied from 5 to 20 MW mainly due to the learning experience with project developers, new project design approaches and use of higher DC capacity of solar field etc. Under Batch-II, only one project has been found more underperforming that might be due to improper O&M or poor design engineering considerations. The average CUF of other 14 PV projects under Batch-II, has been achieved at 21.57%. Out of 15 projects, 2 projects have achieved annual CUF ≥23%, 4 projects reported CUF ≥22%, 12 projects reported CUF ≥21%, 13 projects reported CUF ≥20%, 14 projects reported CUF ≥19% and 1 project reported CUF ≤19%. Typically, TF modules of CdTe and CIS were used under Batch-II by the project developers.

PV projects implemented under migration scheme achieved benchmark performance. Out of five select projects under MS, the average annual CUF reportedly achieved at 20.28%. The performance of the IREDA projects (1 to 2 MW capacity) has not shown remarkable performance. Only 4 projects have been selected for performance evaluation in this study as they provide complete information on project design and energy generation. The average actual CUF of select IREDA projects has been observed at 16.78%. One key reason of low annual performance of IREDA project might be the associated technicality with the policy that all the power evacuation of these projects have been made through 11 kV distribution network which essentially comprises low availability and higher transmission losses; however, for other cases the minimum voltage level has been defined as 33 kV or above at grid substation.

5.2 Technical losses

There are several technical losses (i. e. optical, array and system losses) associated with PV power project that needs to be estimated and addressed realistically during the EYA [81-84]. Optical losses are associated with the conversion of solar irradiance (optical energy) through PV modules into electrical energy under specified design approach (tilted or tracking) [85]. Array losses are within the solar module of the DC field which essentially comprises losses due to temperature, quality, mismatch, degradation, cabling etc. [81, 86]. Finally, system losses comprise DC to AC conversion, losses due to inverters, transformers, AC cables, availability of plant and grid, auxiliaries etc. The range of technical losses associated with select PV projects under various SRDBs has been presented in Table S.3 of the supplementary section. The augmentation of GHI via optimizing the tilt gives the maximum energy yield over the collector plane however the temperature driven losses are most dominant losses in the PV system which are technology and location specific.

5.3 Simulations under different solar radiation databases

In this study, using PV_{SYST} energy yield assessment for PV projects has been carried out after taking into account the relevant technical and design parameters for each SRDB. The DC and AC capacities of select projects have been taken as per their actual project design [76-78]. The key technical losses have been optimized in the PV_{SYST} through best industrial practices and the CUF has been determined accordingly. The CUF obtained from simulations for all SRDBs for PV projects under NSM Phase-I considered in this study are presented in Figure 4. Using the GHI values and climatic conditions of NASA database (Table A.2) the average CUF for select PV projects has been estimated at 18.41% for Batch-I, 19.20% for Batch-II, 18.81% for migration and 19.54% for IREDA projects. NREL database (Table A.2) has shown higher annual average CUF of the PV projects due to higher annual GHI viz. 21.2% for Batch-I, 21.57% for Batch-II, 22.14% for migration and 19.83% for IREDA projects. Annual average CUF using SWERA data (Table A.2) is estimated at 21.15% for Batch-I, 21.71% for Batch-II, 20.7 for migration and 20% for IREDA projects.

The annual performance under time-series databases has been found slightly lower as compared with static satellite databases. Annual average CUF of the PV projects has been estimated at 19.65% for Batch-I, 19.84% for Batch-II, 20.36% for migration and 19.53% for IREDA projects using the GHI values and climatic conditions of Meteonorm 7.0 (Table A.2) weather database. Similarly, annual average CUF of PV projects using Meteonorm 7.1 (Table A.2) weather database has been estimated at 19.27% under Batch-I, 19.71% under Batch-II, 20.94% for migration and 18.33% for IREDA projects. The high-resolution time-series satellite data of SolarGIS (Table A.2) shows the annual average CUF of PV projects at 19.06% for Batch-I, 20.1% for Batch-II, 20.52% for Migration and 18.1% for IREDA projects. The mutual variation of PV projects shows a different range of variation with the actual and estimated CUF of PV projects with different databases as shown in Table S.4.

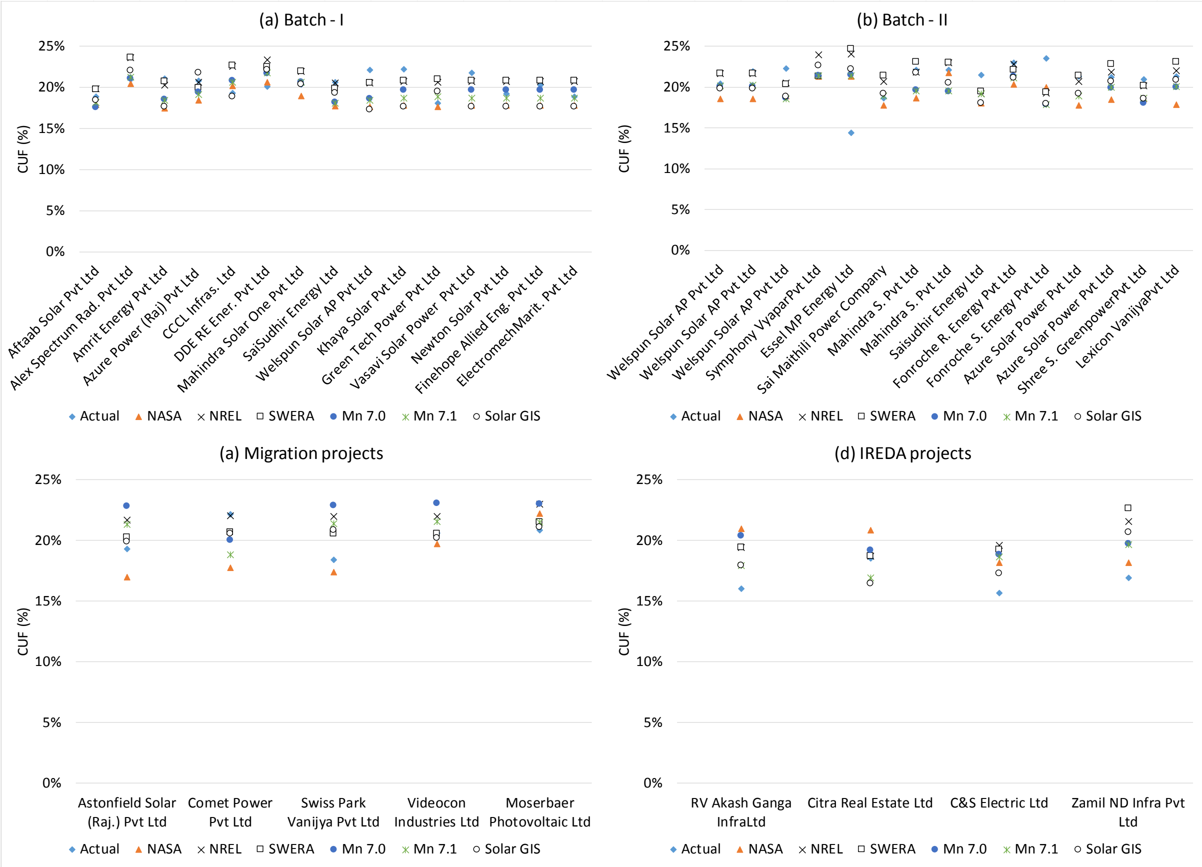


Figure 4: Actual and estimated CUF of solar PV projects using various SRDBs

5.4 Levelized cost of electricity of Solar PV Projects under NSM Phase-I

In order to carry out the impact of mutual variability of the solar resource from different SRDB's over the financial performance of select PV projects, a financial model has been developed in order to estimate the LCOE. Investment and O&M costs of PV projects have been taken from CERC's benchmark capital cost norm for PV projects during 2016-17 [69]. Table S.5 presents the cost break-up of MW-scale PV project taken for financial assessment. The key technical and economic parameters taken into account for the determination of LCOE are presented in Table S.6. Figure 5 presents the LCOE for PV projects under NSM Phase-I under each SRDB. The average LCOE for PV electricity has been estimated at INR 5.33/kWh for 15 select PV projects under Batch-I for actual plant performance. However, the average LCOE under different SRDBs has shown noticeable variance. The average LCOE of PV projects under Batch-I varied from INR 5.12/kWh to INR 5.88/kWh for NREL and NASA database respectively (Figure 5a).

The average LCOE decreases with Batch-II projects as compared to Batch-I projects of NSM Phase-I. For actual generation; the average LCOE is estimated at INR 5.19/kWh. The average LCOE under Batch-II varied from INR 5.01/kWh to INR 5.65/kWh for SWERA and NASA databases respectively (Figure 5b). The average LCOE for actual generation is estimated at INR 5.35/kWh for migration projects whereas LCOE varied from INR 4.86/kWh to INR 5.79/kWh for Meteonorm 7.0 and NASA databases respectively (Figure 5c). LCOE obtained from SolarGIS database has shown close proximity to the actual generation data whereas LCOE for IREDA projects is observed slightly higher than the above-mentioned categories. The average LCOE has been estimated at INR 6.44/kWh with respect to actual energy generation whereas average LCOE varied from 5.43/kWh to INR 6.00/kWh for SWERA and SolarGIS databases respectively (Figure 5d. The mutual scattering within the LCOE of any project is varying differently under all four project implementation categories as shown in Table S.4 of the supplementary section.

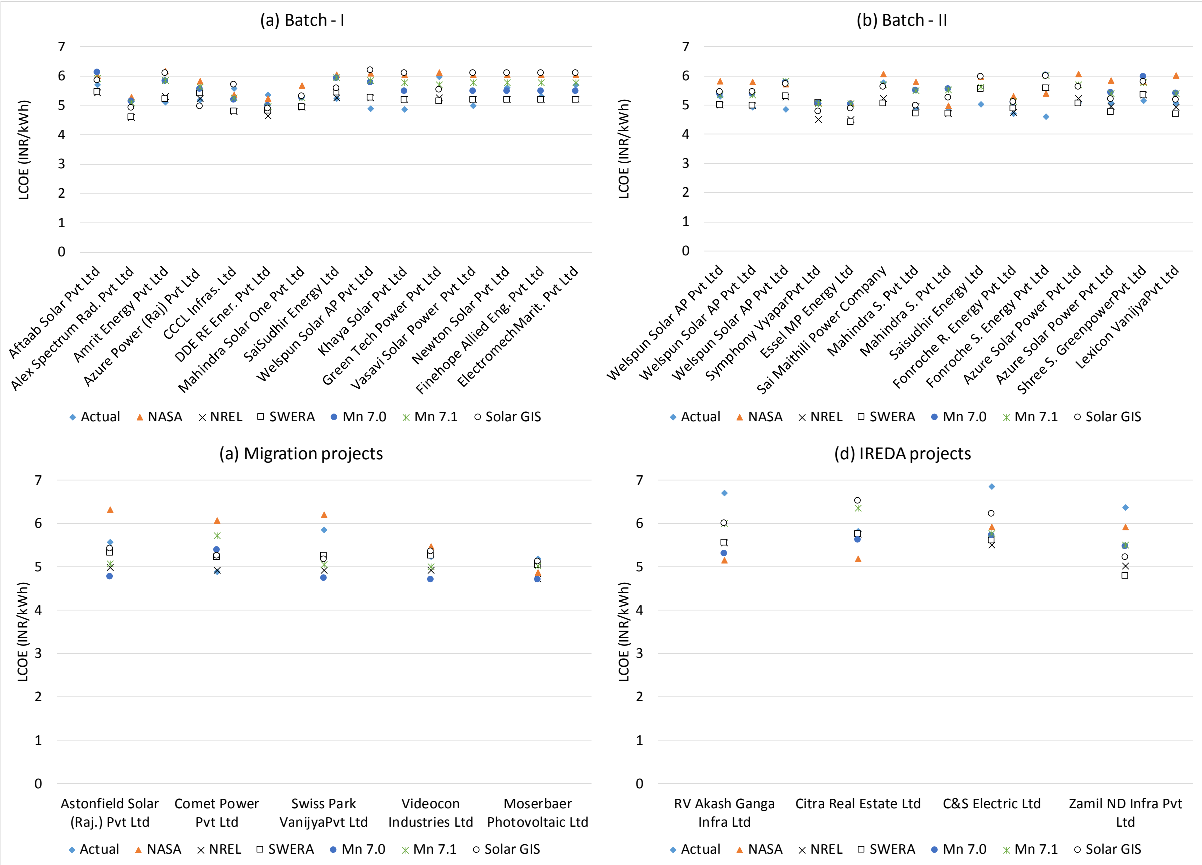


Figure 5: Actual and estimated levalized cost of electricity of PV projects using various SRDBs

6. Mean Absolute Percentage Error of Solar PV Projects

In this section, the mean percentage error (MPE) has been estimated for CUF obtained from simulations under different databases using PV_{SYST} with respect to actual CUF of the PV projects. MPE can be estimated as

$$MPE = \left(\frac{100\%}{n}\right) \sum_{t=1}^{n} \frac{a_t - f_t}{a_t} \tag{5}$$

Where a_t is the actual value of the quantity being forecast, f_t is the forecast, and n is the number of different times for which the variable is forecast.

6.1 Solar PV Projects under NSM Phase – I (Batch – I)

Figure 6 presents the MPE associated with PV projects implemented under NSM Phase-I using several SRDBs presented in Table A.2 of Appendix-I. For Batch-I projects, MPE varied from -20.3% to 4.4% under NASA database. Out of 15 projects under Batch-I, NASA database underestimates the CUF for 13 projects and overestimates CUF for 2 projects as compared to the actual CUF. The 5 MW project of DDE RE Energy Pvt. Ltd. located at Jaisalmer shows the highest closeness of 2.5% followed by the 5 MW project of Green Tech Power Pvt. Ltd. at Bikaner (MPE = -2.6%). Welspun Solar at Kadapa shows a maximum deviation of -20.3% followed by Khaya Solar Pvt. Ltd. (-19.8%) and Vasavi Solar Pvt. Ltd. (-18.2%). 7 projects show MPE≥ 10%, 4 projects show MPE 5-10% and 4 projects show less than 5% MPE with respect to actual plant performance. NREL data overestimate the performance of 9 PV projects and underestimate the performance of 6 projects installed under Batch-I. The range of variation has been observed from -7.3% to 16.8% for NREL database. The database shows the closeness of less than 1.0% for two projects namely 5 MW Azure Power (Raj) Pvt. Ltd. located at Nagaur and SaiSudhir Energy Ltd. at Anantapur (Table S.7). The projects of CCCL Infra Ltd. at Thootikudi and DDE RE Energy Pvt. Ltd. show the maximum deviation of MPE of 16.8% and 16.2% respectively. Out of 15 PV projects under Batch-I, 4 projects show MPE ≥10%, 5 projects show MPE 5-10% and 6 projects show MPE ≤5%. In line with the previous static satellite databases, SWERA database overestimates the plant performance of Batch-I projects. Out of 15 projects, 9 projects overestimate the CUF while 6 projects underestimate the plant performance. The range of variance of Batch-I projects has been observed from -7.3% to 17.1%. For Amrit Energy Pvt. Ltd. project, the database shows the most attractive MPE of 1.8%; however, for the CCCL Infra Ltd. project the deviation is estimated at 17.1% followed by Green Tech Power Ltd. project (MPE ≈16.2%). Under Batch-I, 4 projects show MPE ≥10%, 5 projects show MPE≈5-10% and 6 projects show MPE≤ 5%.

The plant performance is underestimated by the time series databases; while MPE ≤2.0% with estimated and actual plant performance for some projects. The Meteonorm 7.0 database overestimates the performance of 7 projects and underestimates the performance of 8 projects with the range of deviation of MPE varied from -15.8% to 7.9%. The database has shown high closeness between the estimated and actual plant performance for three projects viz. Alex Spectrum Red Pvt. Ltd. located at Bikaner (MPE≈0.1%), Mahindra Solar One Pvt. Ltd. at Jodhpur (MPE≈1.2%) and Green Tech Power Ltd. at Bikaner. The project of Welspun Solar at Anantapur has shown the maximum deviation of -15.8% with Meteonorm 7.0 data followed by the project of Amrit Energy Pvt Ltd. with 12.4% MPE. Out of 15 projects, 4 projects show MPE ≥10%, 5 projects show 5-10% MPE and 6 projects show less than 5% MPE. Similarly, the Meteonorm 7.1 database overestimates the performance of 5 projects and underestimates the performance of 10 projects with the range of deviation of MPE varied from -16.8% to 8.3%. Only 3 projects show MPE ≤2.0% (Table S.7). The project of Welspun Solar at Anantapur shows a maximum deviation of -16.8% with Meteonorm 7.1 database followed by the project of Khaya

Solar Pvt. Ltd. located at Nagaur with -15.9% MPE. Out of 15 PV projects under Batch-I, 5 projects show MPE ≥10%, 4 projects show 5-10% MPE and 6 projects show MPE≤5%.

The MPE with time series SolarGIS database has been experienced ≥20% for two projects. 10 projects underestimate while 5 projects overestimate the plant performance with respect to the actual performance of the PV projects. The range of MPE variance has been obtained from -21.7% to 9.9% with the SolarGIS database. The project of Welspun Solar at Anantapur shown a maximum deviation of -21.7% with SolarGIS data followed by the project of Khaya Solar Pvt. Ltd. with -20.3% MPE. Out of 15 PV projects, 2 projects show MPE ≥20%, 3 projects show MPE≈10-20%, 10 projects show ≤10% MPE. Most of the PV power projects under Batch-I have achieved attractive average annual CUF, therefore no specific issue of O&M has been realized in order to carry out the inter-comparability. It has been observed that the MPE associated with the actual LCOE follow the similar trends of variation as it has been observed for CUF. Significant variation in the inter-comparability of LCOE has been observed through select SRDBs over PV projects under Batch-I. The MPE of LCOE estimated for actual plant performance against estimated generation through different SRDBs has been presented in Table S.7 of the supplementary section. However, the range of MPE under all SRDBs has been presented in Figure 6(a) for the select PV projects under Batch-I.

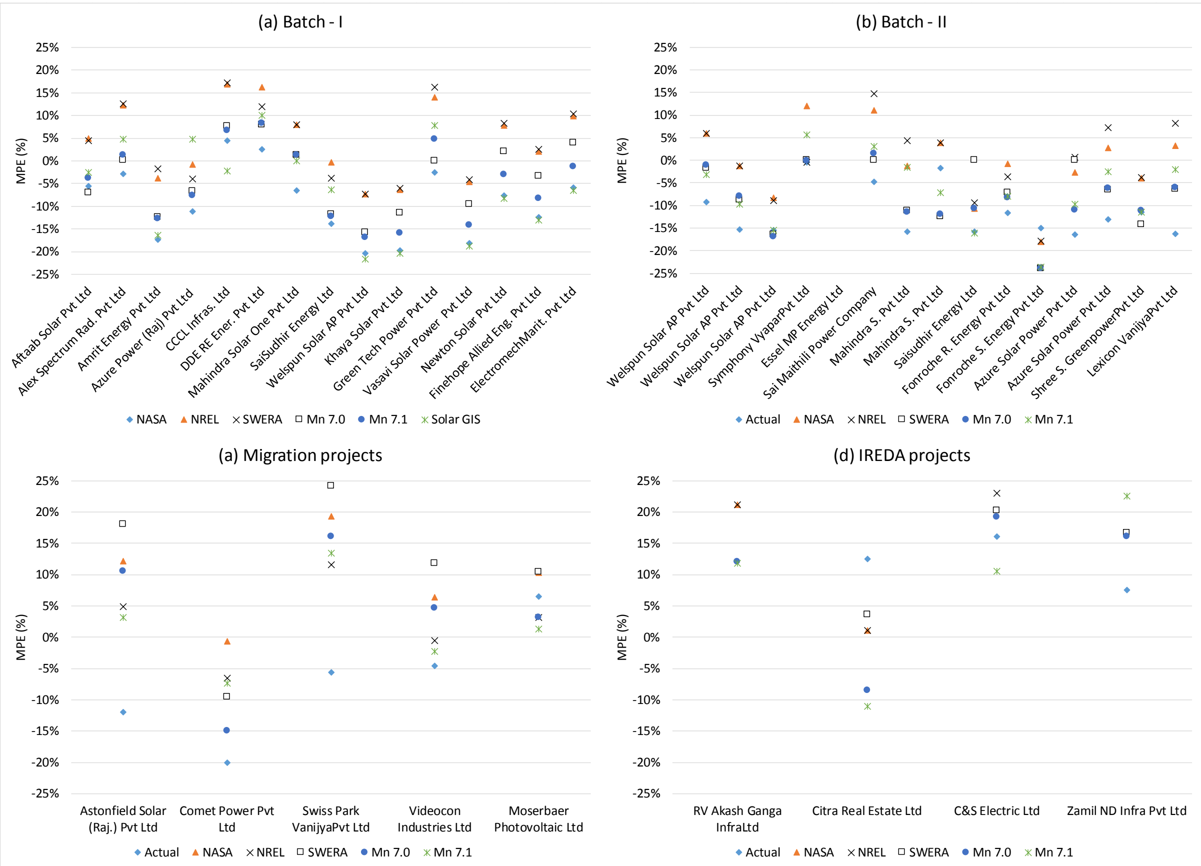


Figure 6: MPE associated with actual and estimated CUF of PV projects through various SRDBs

6.2 Solar PV Projects under NSM Phase-I (Batch – II)

As mentioned above, the minimum capacity of the PV projects has been increased from 5 MW up to 20 MW under the NSM Phase-I, Batch-II. The PV project of 20 MW capacity implemented by Essel MP Energy Ltd. located at Osmanabad has been found underperforming with an annual CUF of 14% and therefore not suitable for inter-comparability. The low performance has been assessed through its low energy generation pattern of last two years which might be due to some technical or O&M issue. Within the MPE variation range of 0.5% to -16.5%, NASA database has been observed underestimating the plant performance for all projects in Batch-II. Out of 14 PV projects from Batch-II, around 10 projects show MPE ≥10%, two projects show 5-10% MPE and the remaining two projects show MPE≤5% using NASA database. On the contrary, the NREL database overestimates the plant performance for 6 projects and underestimate the performance of 8 projects with respect to actual energy generation. The range of MPE has been experienced from -18.0% to 12.14% in which the project of Fonroche S. Energy Pvt Ltd located at Pokhran shows -18% MPE. Out of 14 PV projects, 4 projects show MPE ≥10%, 2 projects with 5-10% MPE and 8 projects with MPE ≤5%. SWERA database also follows the similar trends as NREL database and overestimate the plant performance of 7 PV projects and underestimate the performance of 7 projects as compared to the actual plant performance. The range of MPE has been experienced from -17.83% to 14.84%. There are three specific projects which show high proximity viz. the projects of Welspun Solar (MPE -1.23%) and Symphony Vyapar Pvt. Ltd. (MPE -0.51%), both located in Jodhpur and Azure Solar Power Pvt. Ltd. located at Nagaur (MPE 0.70%). Out of 14 PV projects under Batch-II, 2 projects show MPE ≥10%, 5 projects show 5-10% MPE and 7 projects with MPE lower than 5% under SWERA database.

The time series Meteonorm 7.0 database underestimates the performance of 10 projects as the range of variation of MPE has been experienced from -23.95% to 0.14%. The project of Fonroche S. Energy Pvt. Ltd. located at Jodhpur has shown maximum MPE of -23.95% followed by the project of Welspun Solar at Pokhran with MPE of -16.39%. 4 projects show the maximum closeness of MPE with actual plant performance. Out of 14 projects, 5 projects show MPE ≥10%, 4 projects show 5-10% MPE and 2 projects show MPE less than 5%. Meteonorm 7.1 time series database follow the symmetric pattern of variation as Meteonorm 7.0 and mostly underestimates the plant performance for 13 projects under Batch-II. The range of MPE has been estimated from -24.03% to 1.45%. The project implemented by Fonroche S. Energy Pvt. Ltd. shows highest MPE of -24.03% followed by the project of Welspun Solar at Jodhpur with MPE of -16.93%. The project implemented by Symphony Vyapar Pvt. Ltd. at Jodhpur shows minimum MPE of -0.19% followed by the project of Sai Maithili Power Company, Gurha with MPE of 1.45%. Out of 14 PV projects, 7 projects show MPE≥10%, 4 projects show 5-10% MPE and 3 projects are with less than 5% MPE. The SolarGIS database underestimates the performance of 12 PV projects under Batch-II (out of 14 projects). The range of MPE varied from -23.57% to 5.74%. The project implemented by Fonroche S. Energy Pvt. Ltd. has shown highest MPE of -23.57% followed by the project of Saisudhir Energy Ltd. at Anantapur with MPE of -16.05%. The project of Mahindra Solar Pvt. Ltd. at Jodhpur shows minimum MPE of -1.58% with SolarGIS database. Out of 14 PV projects, 4 projects shows MPE ≥10%, 3 projects show 5-10% MPE and 7 projects show MPE ≤ 5% under SolarGIS time series database.

The variation pattern of MPE associated with CUF of Batch-II projects has been observed slightly different as compared with Batch-I projects mainly due to the capacity variance of the projects. It has been experienced that most of the projects have been implemented in Rajasthan under NSM Phase-I which is essentially 'hot and dry' climatic zone of the country. MPE associated with the LCOE of actual plant performance follow the similar trends of variation as it has been observed for CUF. The MPE of LCOE estimated for actual plant performance against estimated generation through different SRDBs has been presented in Table S.7 of the supplementary section. The range of MPE under all SRDBs has been presented in Figure 6(b) for the select PV projects under Batch-II.

6.3 Solar PV projects under Migration and IREDA Schemes

Under the migration scheme, the project capacity was 5 MW in line with Batch-I, whereas PV project capacities under IREDA scheme were 1 to 2 MW connected to the distribution grid. For 5 PV projects under migration scheme, it is observed that the NASA database underestimate the performance of 4 projects (MPE ≈ -19.98% to 6.53%), NREL database overestimate the performance of 4 projects (MPE ≈ -0.68% to 19.34%) whereas SWERA database underestimate the performance of two projects and overestimate the performance of two projects (MPE ≈ -6.63% to 11.57%). Out of three low-resolution satellite databases for migration projects, SWERA estimates are close to actual energy generation. Meteonorm 7.0 and Meteonorm 7.1 database overestimate the performance of 4 PV projects and underestimate the performance of one project by Comet Power Pvt. Ltd. The MPE range for Meteonorm 7.0 has been estimated at -9.61% to 24.17% to migration projects whereas MPE range is estimated at -15.02% to 16.08% for Meteonorm 7.1. The minimum MPE has been shown by the Moser Baer Photovoltaic Ltd. project for both Meteonorm 7.0 and Meteonorm 7.1 databases. For SolarGIS database, MPE varied from -7.35% to 13.36% under migration scheme. Three projects show MPE ≤3% using SolarGIS database whereas the maximum value of MPE is estimated at 13.36% for Swiss Park Vaniya Pvt. Ltd. project. The range of MPE for CUF of the select PV projects under migration scheme using SRDBs is shown in Figure 6(c).

The projects under IREDA scheme also show significant variation and rather a large deviation as compared with above three categories. IREDA projects are of small capacities as compared to Batch I&II and migration categories, therefore, the technical issues might be different as the actual CUF of all select projects has been reported less than 19% [69]. Key reasons for poor performance possibly due to lower availability of evacuation infrastructure (LT line) or poor O&M practices etc. Table S.7 presents the minimum, maximum and range of deviation of MPE for select IREDA projects under all SRDBs.

The range of MPE for CUF of the select PV projects under IREDA scheme in all select SRDBs is shown in Figure 6(d). It may be noted that MPE associated with the LCOE of actual plant performance follow the similar trends of variation as it has been observed for CUF in both MS and IREDA projects.

7. Conclusions

In this study, the performance of large-scale grid-interactive PV projects implemented under NSM Phase-I has been analyzed. For performance assessment, the actual electricity generation pattern of 39 PV projects of capacity varying from 2 to 20 MW under NSM Phase-I have been considered. PV_{SYST} has been used for EYA of select solar PV projects after taking into account the key design and technical parameters, and associated energy losses during solar energy conversion. All NSM Phase-I (Batch-I) projects achieved average CUF of 20.33% that is higher than its benchmarked value of 19% provided by CERC [69]. In Batch-II, except two projects, the CUF of select PV projects was more than the CERC benchmark value. In contrast to the IREDA projects, PV projects under migration scheme show higher CUF as compared to the CERC benchmark value. Technical simulations have been carried out for all 39 project location using static (NASA, NREL, SWERA) and dynamic (Meteonorm, SolarGIS) solar irradiance data from various databases available in the Indian context. The capacity factor of select PV projects under time-series databases has been found slightly lower as compared with static satellite databases. Mutual deviation of techno-economic performance of PV projects operational under Phase-I of NSM varied from -14% to 27% for the projects under Batch-I, and -12% to 31% for the projects under Batch-II. It is observed that all databases either underestimate or overestimate the performance of select PV projects installed under NSM Phase-I. Therefore, it is essential for all databases to mention specific uncertainty associated with the data which could be considered during probability assessment. The quantum of solar irradiance is the key region for deviation. For bankability of solar power projects, availability of long-term solar radiation data over the potential locations of India as well as other developing countries is a key barrier. Therefore, the project developers should give more preference to long-term measured or high-resolution satellite time series databases.

In Indian solar market, any standard ranking of solar radiation databases is not available therefore project developers adopt the solar radiation databases randomly. The random approach of resource assessment makes a significant impact on the techno-economic viability of the projects. Overestimation of the plant performance at design stage may lead to more financial risk for project developers and lenders due to an expansion of project payback period and loan repayment. At present, in utility-scale solar power market of India the tariff through competitive bidding is drastically reducing, therefore, quality control and bankability of solar PV projects is a key challenge. On the other hand, underestimation of the plant performance could make the project more challenging to achieve financial closure but minimize the risk of lenders. Among all parameters (resource, technical and operational), the solar resource comprises maximum uncertainty in order to carry out the bankable energy yield estimation of PV power projects. There are several projects in the country which are facing the problem of low performance against estimated at the design stage. The EPC contractors agree with the implementation of additional solar field or paying of revenue loss to the project developer in case of the lower generation. Meeting the plant performance criteria with the effectively decreasing tariff and benchmark codes and standards is a major challenge to the project developers; hence the risk associated with resource assessment needs to be minimized.

With the increasing share of solar and wind power (intermittent) in the overall energy mix; the Indian government is in the advance stage of implementing scheduling and forecasting on renewable power projects from the point of view of power quality and grid stability. In order to address these aspects, the time series data with small intervals is essential. Since the availability of long-term solar radiation data over the potential locations of India is a key barrier it could be recommended that the project developers and lender should give more preference to long-term time series databases. The solar power policies of the country must provide clear guidelines for selection of solar radiation databases to enhance their bankability.

The results of this study are also useful for other developing and emerging economies with the unavailability of long-term solar radiation data over the potential locations. Therefore, it is critically important to ensure the highest degree of confidence in the techno-commercial due diligence of a utility-scale solar PV power project as the tariff of solar power is drastically reducing. Further, precise assessment of solar radiation and use of high-resolution long-term time series databases may help project developers to make more accurate scheduling and forecasting of energy generation to grid operators.

Acknowledgements

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Appendix-I

Table A.1. Technical details of the select Solar PV power projects under NSM, Phase-I [76-78]

Project/Location (District, State)	Lat. (ºN)	Lon. (ºE)	Project capacity (MW)	COD*	Solar PV Module			Inverter (Manufacturer/Rating)	Tilt Angle (deg.) due south
					Techno logy	Manufacturer	Model/ Rating (Wp) / Numbers		
Batch-I projects									
1. Aftaab Solar Pvt Ltd, Bolangir, Orissa	20.74	83.48	5	02/2012	TF	First Solar	FS-380 (80 Wp)	SMA (Sunny Central -800 CP)	25
2. Alex Spectrum Radiation Pvt Ltd, Bikaner, Rajasthan	28.13	72.95	5	02/2012	TF	First Solar	FS-377 (59580 Nos.)/ FS-380 (4860 Nos.)/ FS-385 (2880 Nos.)	SMA (6 /RPS 830 TL) (1/RPS 570 TL)	30
3. Amrit Energy Pvt Ltd, Bhilwara, Rajasthan	25.85	74.65	5	02/2012	TF	First Solar	FS-377 (40,558 Nos.), FS-380 (22,344 Nos.), FS-382 (5,873 Nos.)	SMA (Sunny Central -800 CP)	30
4. Azure Power (Rajasthan) Pvt Ltd, Nagaur, Rajasthan	27.21	75.25	5	01/2012	TF	First Solar	FS-270 (351 Nos.)/ FS-272 (1247 Nos.) /FS-275 (19120 Nos.) / FS-277 (34985 Nos.)/ 280 (11043 Nos.)	SMA (Sunny Central -800 CP)	30
5. CCCL Infras. Ltd, Thoothkudi, Tamil Nadu	9.28	78.6	5	03/2012	TF	Solar Frontier	SF 130 (33360)	Power-One (500 KW)	10
6. DDE Renewable Energy Pvt Ltd, Jaisalmer, Rajasthan	27.38	71.72	5	02/2012	MC	Lanco Solar	LSP 230 (174 Nos.)/ LSP 235 (11784 Nos.)/ LSP 240 (7432 / 3552 With Tracking)/ 245 (434 Nos.)	Bonfiglioli (RPS TL 1000)	30
7. Mahindra Solar One Pvt Ltd, Jodhpur Rajasthan	27.5	72.4	5	01/2012	CR	Sunpower	SER 228	Siemens (PVS 2400)	30
8. SaiSudhir Energy Ltd, Anantapur, Andhra Pradesh	14.68	77.6	5	01/2012	TF	Solar Frontier	SF 145-S (34,483)	AEG P S (Protect-PV 500)	30
9. Welspun Solar AP Pvt Ltd, Kadapa Andhra Pradesh	14.46	78.23	5	01/2012	TF	Solar Frontier	SF-150-S (36,664 Nos.)	Power-One Aurora (PVI-500)	
10. Khaya Solar Pvt Ltd, Nagaur, Rajasthan	27.36	71.73	5	01/2012	MC	Lanco Solar	LSP 230 (230 Wp)	Helio Systems (HIS 640)	30
11. Green Tech Power Pvt Ltd, Bikaner, Rajasthan	27.83	72.95	5	02/2012	PC	Waaree	WS 280 (280 Wp)	ABB (500KW)	15
12. Vasavi Solar Power Pvt Ltd, Jaisalmer, Rajasthan	27.38	71.72	5	02/2012	MC	Lanco Solar	233 Wp (1120 Nos.)/ 235 Wp (12768 Nos.)/ 236 Wp (2800 Nos.)/ 239 Wp (4200 Nos.)/ 240 Wp (1800 Nos.)/ 242 Wp (560 Nos.)	Bonfiglioli (RPS TL 1000)	30
13. Newton Solar Pvt Ltd, Jaisalmer, Rajasthan	27.37	71.75	5	02/2012	MC	Lanco Solar	LS 230 (230 Wp)	Helio Systems (HIS 640)	30
14. Finehope Allied Engineering Pvt Ltd, Jaisalmer, Rajasthan	27.36	71.73	5	02/2012	MC	Lanco Solar	LS 235 (235 Wp)	Bonfiglioli (RPS TL 1000)	30
15. Electromech Maritech Pvt Ltd, Jaisalmer, Rajasthan	27.37	71.75	5	02/2012	MC	Lanco Solar	LSP 230 (230 Wp)	Bonfiglioli (RPS TL 1000)	30
Batch-II projects									
1. Welspun Solar AP Pvt Ltd, Jodhpur, Rajasthan	27.06	72.23	20	01/2013	TF	First Solar	FS 385	SMA (SMA 800 CP)	30
2. Welspun Solar AP Pvt Ltd, Jodhpur, Rajasthan	27.06	72.23	15	01/2013	TF	First Solar	FS 385	SMA (SMA 800 CP)	30
3. Welspun Solar AP Pvt Ltd, Jodhpur, Rajasthan	27.06	72.23	15	01/2013	TF	First Solar	FS 385	SMA (SMA 800 CP)	30
4. Symphony VyapaarPvt Ltd, Jodhpur, Rajasthan	27.06	72.23	10	01/2013	PC	Vikram Solar	240, 245	Schneider (XC 680)	30
5. Essel MP Energy Ltd, Osmanabad, Maharashtra	17.81	76.25	20	01/2013	TF	Nex Power	NT-155 AX (155)	Schneider (500 KW)	15
6. Sai Maithili Power Company, Gurha, Rajasthan	27.86	72.83	10	02/2013	TF	Miasole	MS140GG-02 (140)	SMA (SMA 800 CP)	30
7. Mahindra Surya Prakash Pvt Ltd, Jodhpur, Rajasthan	27.38	72.21	20	02/2013	TF	First Solar	FS 385	SMA (SMA 800 CP)	30
8. Mahindra Surya Prakash Pvt Ltd, Jodhpur, Rajasthan	27.38	72.21	10	02/2013	TF	First Solar	FS 385	SMA, (SMA 800 CP)	30
9. Saisudhir Energy Ltd, Anantapur Andhra Pradesh	14.6	77.2	20	02/2013	TF	Solar Frontier	140 Wp (2 MWp)/ 145 Wp (2 MWp) / 155 Wp (18 MWp)	AEG Power Solutions (Protect PV.630)	15
10. Fonroche Raajhans Energy Pvt Ltd, Pokhran, Rajasthan	27.96	73.03	5	12/2012	TF	First Solar	FS 382 (67,200)	Schneider (XC 680)	30
11. Fonroche Saaras Energy Pvt Ltd, Pokhran, Rajasthan	27.96	73.03	15	02/2013	TF	First Solar	FS 382 (203100)	Schneider, (XC 680)	30

12. Azure Solar Power Pvt Ltd, Nagaur, Rajasthan	27.25	74.27	20	02/2013	TF	First Solar	FS 385	SMA (SMA 800 CP)	30
13. Azure Solar Power Pvt Ltd, Nagaur, Rajasthan	27.25	74.27	15	02/2013	TF	First Solar	FS 385	SMA (SMA 800 CP)	30
14. Shree SaibabaGreenpowerPvt Ltd, Latur, Maharashtra	18.40	76.56	5	02/2013	TF	Nex Power	NT100, NT140, NT145	Schneider (500 KW)	15
15. Lexicon VanijyaPvt Ltd, Jodhpur, Rajasthan	27.79	72.19	10	02/2013	PC	Vikram Solar	230 (235)	Schneider (500 KW)	30
Migration Projects									
1. Astonfield Solar (Rajasthan) Pvt Ltd, Jodhpur, Rajasthan	26.51	72.68	5	03/2012	TF	T Solar	TS390	Schneider (500 KW)	30
2. Comet Power Pvt Ltd, Jaisalmer, Rajasthan	26.01	72.98	5	10/2011	MC	Sun Tech	STP 280-24/Vb	SMA (Sunny Central 720CP)	30
3. Swiss Park VanijyaPvtLtd, Jodhpur, Rajasthan	26.53	72.85	5	10/2011	TF	T Solar	TS390	Schneider (500 KW)	30
4. Videocon Industries Ltd, Latur, Maharashtra	24.74	75.51	5	02/2012	TF	First Solar	FS 385	SMA (SMA 800 CP)	15
5. Moser Baer Photovoltaic Ltd, Jodhpur, Rajasthan	26.70	72.90	5	02/2013	TF/ MC	Moser Baer	MBTF400350 to MBTF400390	SMA (SMA 800 CP)	30
IREDA projects									
1. RV Akash Ganga InfraLtd, Haridwar, Uttarakhand	30.01	78.13	2	01/2012	TF	First Solar	FS 385	SMA (SMA 800 CP)	30
2. Citra Real Estate Ltd, Nagpur, Maharashtra	21.15	79.04	2	01/2012	MC	BHEL		Schneider (500 KW)	15
3. C&S Electric Ltd, Bhiwani Haryana	28.78	76.13	1	06/2011	MC	EMMVEE		Efacec	30
4. Zamil ND Infra Pvt Ltd, Jodhpur, Rajasthan	26.71	72.90	1	01/2012	TF	First Solar	FS 385	SMA (SMA 800 CP)	30

*COD: Commercial Operation Date; TF: Thin Films; MC: Multi-Crystalline

Table A.2. Solar radiation databases in the Indian context

S. No.	Database	Type of database	Properties	Remarks
Ground (Measured) Databases				
1.	IMD database - Indian Meteorological Department (IMD), Ministry of Earth Sciences, Government of India	Static (monthly average daily)	IMD has published following four databases (for 18-23 locations of the country) in the context of India in which the solar radiation data has been reported in static/dynamic formats: • Solar radiation over India (1980) – *18 locations hourly measured* • Handbook of Solar radiation (1982) – *145 locations computed* • Handbook of Solar Radiation over India (2008) – *23 locations measured* • Solar Radiant Energy over India (2009) – *23 locations hourly measured*	Weather stations are mainly located in cities however solar power project locations are too far from the location of weather stations. The long-term data is available for IMD locations from National Data Center, Pune commercially. The database is not well adopted by industries for utility-scale SPPs but could be effectively used for rooftop solar projects in the respective cities.
2.	SRRA database - Solar Radiation Resource Assessment (SRRA), National Institute of Wind Energy (NIWE), Government of India		Solar radiation data along with weather parameters available for 115 stations across the country.	NIWE data is commercially available for selected locations in time series formats. Since data is short-term from 3 to 5 years; till date developers have not adopted the database aggressively in the country. NIWE is also working on a mix of the high-resolution data with ground data towards the development of high-resolution maps for India.
Satellite (Low Resolution) Databases				
3.	NASA database - Surface Meteorology and Solar Energy Database	Static (monthly average daily)	Low-resolution satellite-derived monthly average daily data for a grid of 1^ox1^o covering the globe for 22 year period (from the year 1983-2005).	Due to low spatial resolution, the database is not recommended for utility-scale projects. However, it is a suitable tool for carrying out pre-feasibility studies of solar power systems. There are several tools (viz. PV_{SYST}, RETScreen, HOMER etc.) which are linked with NASA satellite database. This database is freely accessible.
4.	SWERA database - Solar and Wind Energy Resource Assessment		SWERA data is based on the geostationary satellites while the database has been developed by UNEP. Solar radiation data is available with a spatial resolution of around 40km x 40km.	SWERA data is freely accessible in the form of digital maps. SWERA has not been used by utility-scale solar industry but frequently used for pre-feasibility studies and evaluation of small solar systems.
5.	SEC-NREL database - Solar Energy Center (SEC)/National Renewable Energy Laboratory (NREL) Database		NREL and SEC (now renamed as National Institute of Solar Energy) have developed solar radiation maps (GHI/DNI) of India with a resolution of 10 km. NREL developed solar radiation maps for monthly and annual GHI data using the hourly satellite data spanning from January 2002 to December 2008 generated through application of the Sunny satellite to irradiance model.	The solar radiation data (GHI/DNI) is freely available at the Ministry of New and Renewable Energy (MNRE) website. The data is mainly used for inter-comparability and pre-feasibility studies. Due to high associated uncertainty, the database has not been well adopted by utility-scale SPPs.
Satellite (Interpolation and high-resolution) Databases				
7.	National Renewable Energy Laboratory (NREL) database	Dynamic – time series (hourly) data in Typical Meteorological Year (TMY) Formats	Hourly annual solar radiation data available for other meteorological parameters in CSV format with a resolution of 10km x 10km.	This database is freely available but not being used by solar project developers of the country due to low resolution and higher associated uncertainty. It is suitable for pre-feasibility of solar projects.
	Meteonorm 6.0, 7.0, 7.1 database		This is an interpolated global solar resource database. Meteonorm software enables the production of TMY for any location of the globe. The database includes a database for solar radiation from 1991-2010 where a location is over 10 km from the nearest weather measurement station; a combination of	The database is accessible through software which generates interpolated time series data in desired formats. The database has been well adopted by solar power industry of India and most of the projects have been implemented using this database. The database is

			ground and satellite measurement are used. The software also presents the associated uncertainty at different probabilities.	user-friendly and addresses validation with ground data, uncertainty etc.
8.	SolarGIS database		Solar radiation data is available for latitudes between 60º N to 50º S at a spatial resolution of 250 meters. The solar resource parameters are calculated from satellite data, atmospheric data and digital terrain models. The nominal time of the data product is 15 min instantaneous and 60 min average values. Solar resource data are available from years 1994, 1999 or 2006 up to the present time.	The database addresses most of the requirements of bankability hence it is widely adopted database by industry for utility-scale solar power projects. SolarGIS addresses the uncertainty and furnishes the data at different probabilities as well. It is commercially available in static and dynamic formats. It has more than 180 locations globally for validation.
9.	Vortex database		It is an on-line modeling service which provides solar radiation and meteorological data derived from mesoscale modeling and satellite information. It provides solar radiation required for the simulation within PVsyst, with a spatial resolution of 3 km.	Vortex is a well-known database in wind sector and recently started solar resource assessment. It is a high-resolution database that is comparable to SolarGIS; however, till date, the solar power project developers have not used this database in practice.
10.	3Tier database		The database has global coverage between 48ºS to 60º N with spatial maps and hourly time series of irradiance at a spatial resolution of 3 km approximately. The location-specific data is available from 1997, 1998 or 1999 up to the current date.	The database is well established for wind resource assessment. Further, the high-resolution data is validated through 120 reference stations.