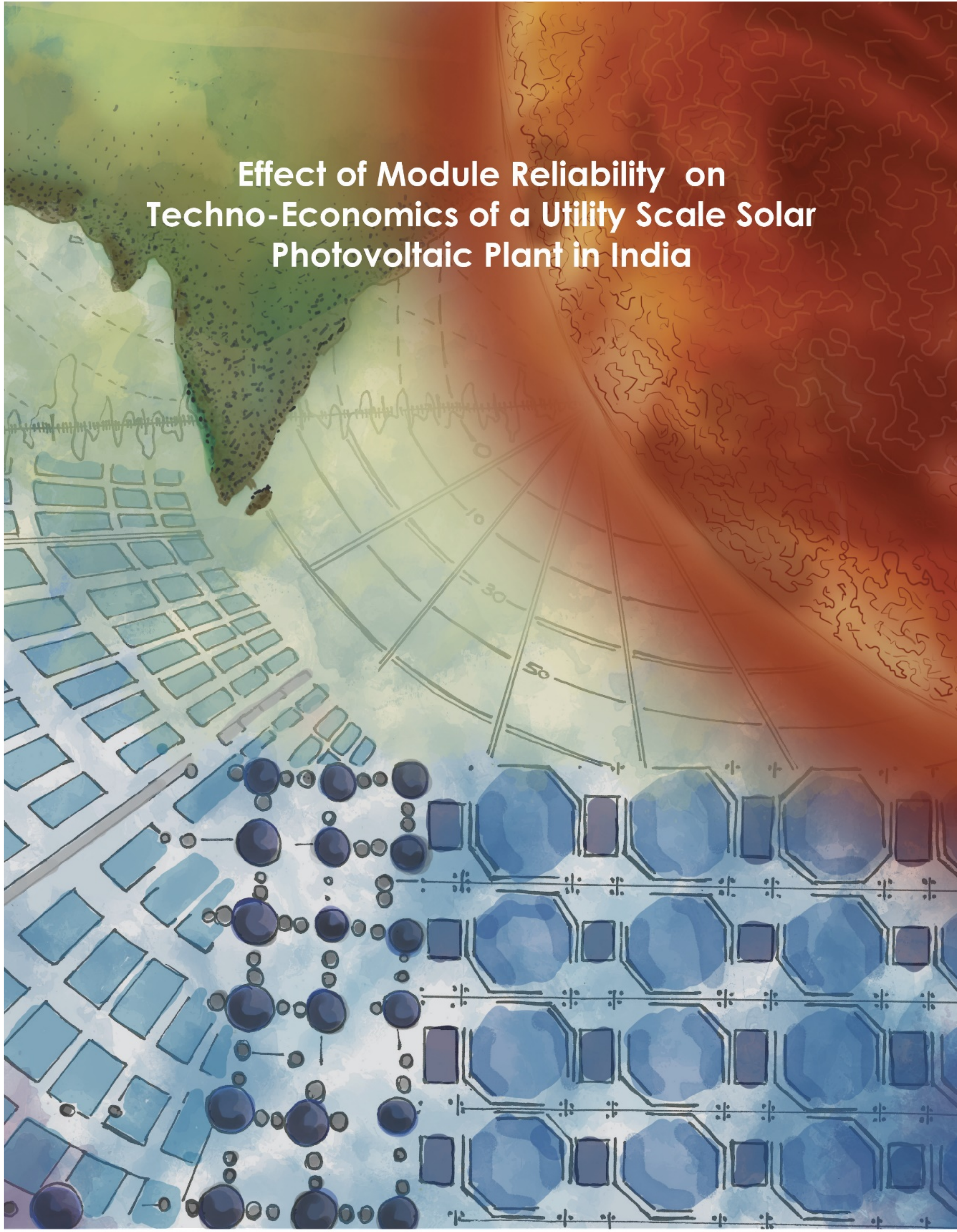
Effect of Module Reliability on Techno-Economics of a Utility Scale Solar Photovoltaic Plant in India



SERIIUS Solar Energy Research Institute for India and the United States

CSTEP Center for Study of Science, Technology & Policy

Effect of Module Reliability on Techno-Economics of a Utility Scale Solar Photovoltaic Plant in India

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Center for Study of Science, Technology and Policy (CSTEP)

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Executive Summary

India has set an ambitious target of 100 GW of solar energy powered systems by 2022. Of this 100 GW, solar photovoltaic (PV) based systems are expected to contribute the major share. The dust and aerosol optical depth observed in India is significantly high. This can affect the performance of PV systems. Further, there is also loss in performance due to degradation of modules. With increasing contribution of solar PV based systems in our energy mix, it is crucial to understand their vulnerabilities. The soiling losses and module degradation are particularly of interest. The former is dependent on cleaning cycle (maintenance practices) and the later affects the long term technical and financial viability of the plant.

These crucial aspects need to be thoroughly examined. In this context, Center for Study of Science, Technology and Policy (CSTEP) built the CSTEM-PV (CSTEP's Solar Techno-Economic Model for Photovoltaics) under the Solar Energy Integration (SEI) research thrust of the Solar Energy Research Institute for India and the United States (SERIIUS). This model serves as a useful tool for prefeasibility analysis of utility-scale solar photovoltaic plants from a techno-economic standpoint, taking into account the effect of module degradation. This report examines the following three aspects:

1. What is the effect of standard module degradation on plant techno-economics, for locations spread across different climate zones?
2. What is the permissible rate of annual module degradation such that the plant remains financially viable?
3. What is the effect of the cleaning cycle on plant techno-economics (via soiling losses)?

Major insights with respect to effect of module degradation and soiling losses from the study are as follows:

- Levelised Cost of Energy (LCOE) is a prominent metric that captures the trade-off from the technical modelling and financial fronts. Critical module degradation rate limits can be identified in terms of the ability to service debt obligations and maintain profitability. Considering the case simulated for the plant (Mumbai), it was identified that:
    - The plant is not financially viable within its lifetime if the module degradation rate exceeds 4% per annum (p.a.).
    - The plant cannot meet its debt obligations if the degradation rate exceeds 3% p.a.
    - The plant may not be profitable if the degradation rate exceeds 2% p.a.
- The cleaning cycle has a measurable effect on plant techno-economics (via soiling losses). For the case simulated (Mumbai), it was observed that, for each day of increase in the cleaning cycle frequency, the LCOE of the plant increases by around 1 paisa/kWh.

- Also a generic insight of interest: It was observed that the plant area requirement increases for higher latitudes (considering module tilt to be equal to the tilt angle).

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1. Introduction

Solar photovoltaic (PV) technology is among the front-runner clean energy technologies for meeting energy needs. India has been taking advantage of its solar energy potential of 749 GW (MNRE, 2017), with the installed solar capacity in the country growing at an unprecedented rate from 1.7 GW (2012) to 17 GW (as on January 2018) (CEA, 2018). The government's ambitious target of 100 GW (60 GW utility and 40 GW rooftop solar) of solar-based capacity addition by 2022 is a clear indication of the market adoption of this technology.

In this regard, it is imperative to understand the vulnerabilities of this technology. In this report, we focus on two such aspects, the effect of soiling losses and module degradation on plant performance. The former is a consequence of the maintenance practice adopted (in terms of cleaning cycle) and the latter captures an effect which is prevalent throughout the life time of the plant. Understanding the impact of these effects on the techno-economics of a plant can help in framing suitable maintenance practices and module quality assessment measures.

In this pursuit, a model providing quick insights relating to prefeasibility and planning of PV technology could help policymakers, researchers and industry trackers make informed decisions. Keeping this in mind, CSTEP built the web-based interactive tool CSTEM-PV[1] (CSTEP's Solar Techno-Economic Model for Photovoltaics). The objective of the tool is to perform an engineering economic assessment for prospective solar PV plants in India based on *publicly available* data via equipment datasheets. *For better understanding and completeness, aspects related to plant design have also been covered in this report.* Figure 1 presents an overview of the model inputs and outputs in CSTEM-PV, while Figure 2 illustrates a simplified process flow of the framework.

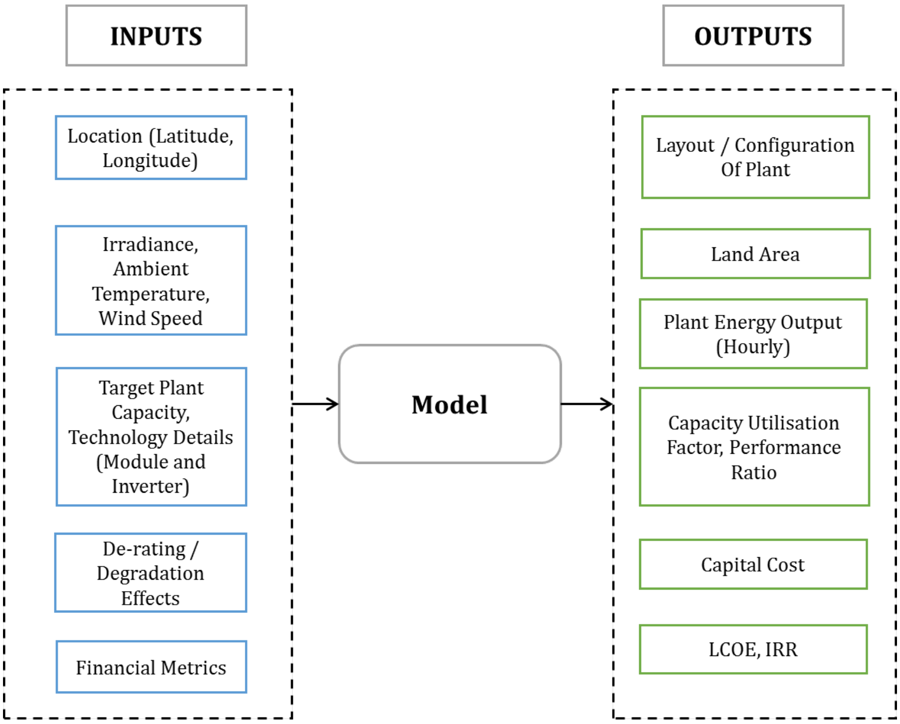

Figure 1: Inputs and outputs of the CSTEM-PV modelling framework

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[1] Web tool is available at http://cstem.cstep.in/cstem/

Using this tool, CSTEP analysed the effect of module reliability and soiling losses on plant techno-economics using site data (for module degradation and soiling losses) provided by IIT Bombay.

The base inputs for the model include location details (latitude and longitude) and the target plant capacity. The size (including dimensions) of module and Power Conditioning Units (PCUs) or inverters can be considered as per the datasheets provided by the respective manufacturers. The financial parameters (like loan term, tax, debt and equity rates etc.), consideration for depreciation rates and capital cost details form the main inputs of the economic model.

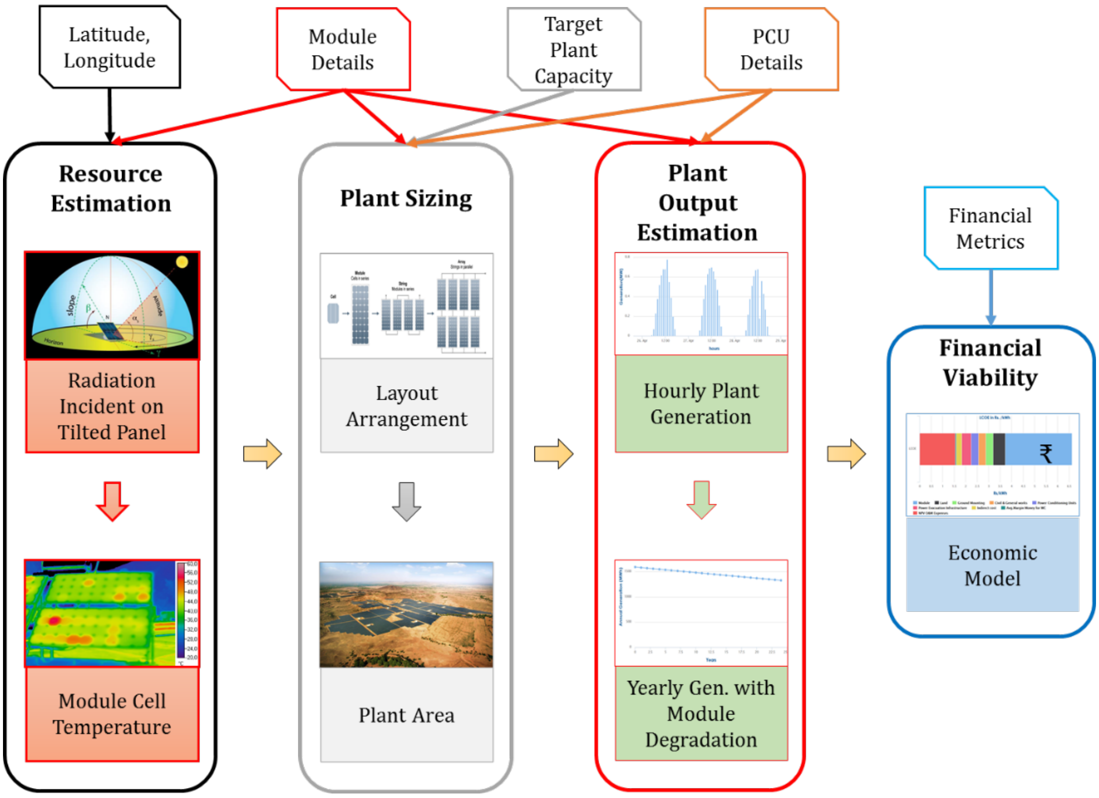

Figure 2: Simplified process flow of the framework

Image sources: Azure Power, 2015; CSTEP, 2017; Paiva, Pimentel, Marra, & de Alvarenga, 2015; Tsanakas & Botsaris, 2009; Your Home (Govt. Of Australia), n.d.

The economic model considered here is as per the method adopted by the Central Electricity Regulatory Commission (CERC) of India (CERC, 2016)[2]. The following points summarise the computational flow performed by the tool after receiving the appropriate inputs:

- The reference for all calculations is in solar time. Hence, if the hourly solar resource data of choice is in zone time, the tool computes the appropriate time shift and maps it to corresponding solar time[3]. It then performs solar geometry calculations. This

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[2] A paper illustrating the working details of the techno-economic model will soon be published on the CSTEP website (Sridhar & N. C., 2018).

[3] This is because of the difference in latitudinal and longitudinal displacement of the location from the location of time reference.

includes computation of various solar angles (declination, hour angle, zenith, surface azimuth, solar azimuth, angle of tilt etc.) for a given location to model the path of the sun with respect to the tilted module (Duffie & Beckman, 2013; Iqbal, 1983; Stine & Geyer, 2001). Based on the module and solar resource details, the effective radiation incident on the tilted module and the cell temperature developed in the module are estimated (King, Boyson, & Kratochvil, 2004).

- The arrangement of modules (parallel and series) should match the chosen current and voltage limits of the PCU[4]. Hence, we choose the reference points[5] carefully to achieve a suitable plant configuration. The configuration here refers to details such as the number of panels per PCU in series and parallel combination. The reference voltage of the PCU limits the number of panels in series, whereas the current limit at the reference voltage of the PCU limits the number of panel strips in parallel. The considerations for this aspect have been well discussed in literature (Hegedus & Luque, 2011; Honsberg & Bowden, n.d.; Kalogirou, 2009; Markvart & Castaner, 2013; Mertens, 2014; Roger & Jerry, 2005; Solanki, 2015 and Teodorescu, Liserre, & Rodriguez, 2011). All of these aspects were accounted for in the model.
- The tool computes the inter-row and inter-column spacing between arrays for a given plant capacity, latitude and time window of operation and determines the total area required by the plant.
- Next, we estimate the power generated by the modules with respect to plant configuration. Further, we modify the plant configuration to suit the location such that at no point the power output exceeds the combined rating of the PCUs. The works of Bai et al., 2015; De Soto, 2004; Townsend, 1989 and Whitaker et al., 1991 were considered in building this aspect of the model.
- The tool also estimates the effect of module degradation on power and then computes the net plant energy output over its useful life.
- Finally, the tool estimates the Levelised Cost of Energy (LCOE) and Internal Rate of Return (IRR). The works of Brigham & Houston, 2007; Cambell, 2008 and CERC, 2016 were taken into account for developing this economic model.

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[4] PCU or the Power Conditioning Unit is generally referred to as the inverter. It is the most crucial component of the PV plant. Also referred to as the brain of the PV plant, its primary function is to convert DC power output from the module combination to the appropriate AC power output that can be fed to the grid.

[5] The voltage and current levels of both the modules and the PCU

2. Sensitivity Analysis: Considerations

We perform a sensitivity analysis to understand the variation in plant sizing for four locations spread across different climate zones in India (details presented in Table 1), considering the effect of ambient temperature, soiling losses, module degradation and cleaning cycles. The difference in the annual solar radiation, average ambient temperature and average wind speeds seen by different locations captures the variation in the spread of solar resource.

A target plant capacity of 1 MWp is simulated considering a 250 Wp multi-crystalline module (Tata Power Solar, 2015) and a 250 kW (Eaton, 2015) PCU as reference for this analysis. Details of both are provided in the Appendix. The solar radiation (GHI) at the selected locations is presented in Figure 3[6] (Ramaswamy, Rao, Thirumalai, & Suresh, 2013). Figure 4 and Figure 5 illustrate the location-specific wind speeds and ambient temperatures. Ladakh receives the highest solar radiation among the four locations, followed by Bhavnagar, Bengaluru and finally Mumbai. On the other hand, the highest hourly average wind speed and ambient temperature is seen by Bhavnagar followed by Bengaluru. Ladakh also, observes the lowest hourly average ambient temperature. The combination of good solar radiation and low ambient temperatures (as seen in Ladakh) is ideal for power generation using solar PV technology. This aspect will be further explained in later sections.

Table 1: Summary of the locations considered for the case studies

Location	Climatic Zone	Latitude (ºN)	Longitude (ºE)
Ladakh	Mountain	34.05	77.75
Bhavnagar	Semi-arid	21.75	72.15
Mumbai	Tropical wet	19.12	72.54
Bengaluru	Tropical wet and dry	12.97	77.35

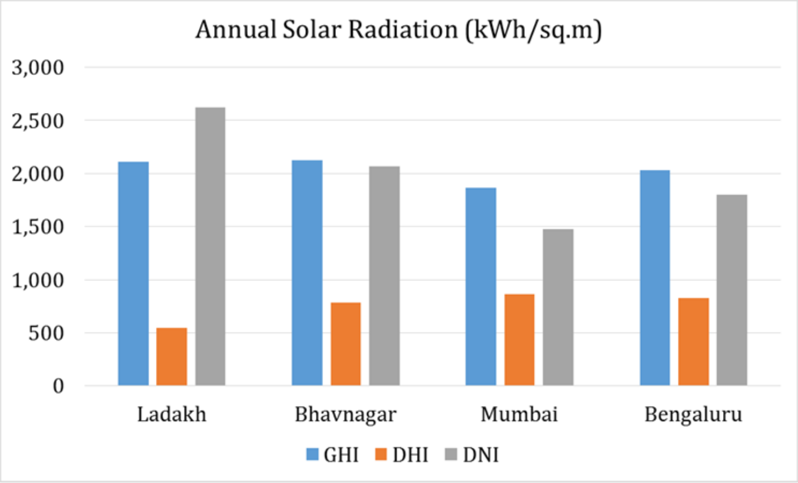

Figure 3: Location-wise annual solar resource availability

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[6] The solar resource data for Ladakh was obtained from the National Solar Radiation Data Base (NSRDB) built by National Renewable Energy Laboratories (NREL). https://nsrdb.nrel.gov/

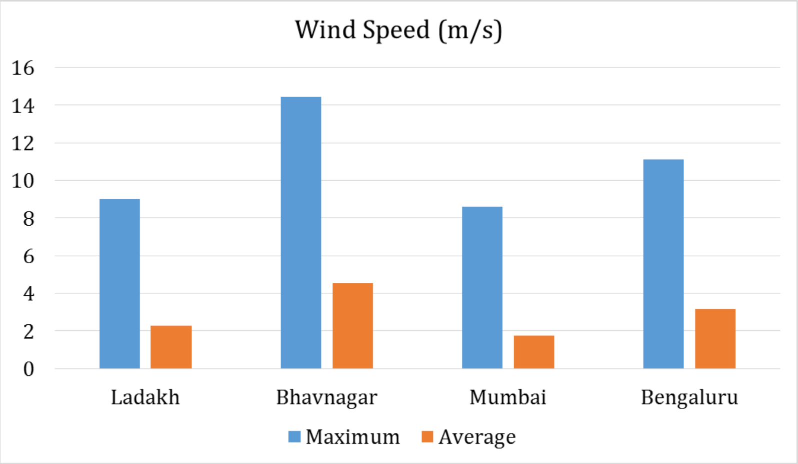

Figure 4: Location-wise annual average and maximum wind speed

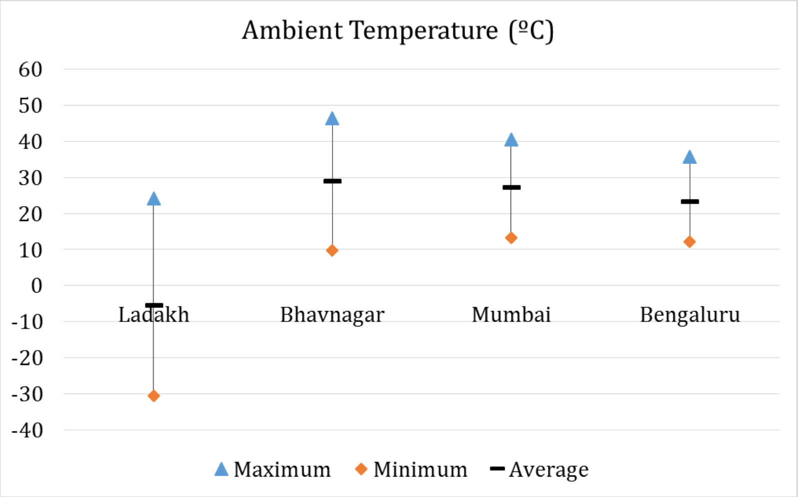

Figure 5: Location-wise spread of ambient temperature

2.1 Assumptions for Technical Model

The technical model comprises several parameter inputs, which are subject to the following assumptions and considerations:

- The plant is designed for a fixed-tilt configuration. The tilt of the module is assumed to be equal to the latitude of the location, and the module is oriented to face due south. The module is further considered to have a glass/cell/polymer sheet module with an open rack mount.
- The array height is considered to be 2 m, that is, 1.5 m of array structure height with 0.5 m of ground clearance.
- The benchmark area considered for optimisation and time window determination is 5 acres per MWp.
- The midpoint of the maximum power point voltage range of the PCU and the maximum power point voltage of the module is chosen as the reference design point for power rating.

- The losses considered are as follows:
    - DC losses
        - Soiling loss = 1%
        - Mismatch loss = 2%
        - Conductor loss = 5%
    - AC losses
        - Conductor loss = 5%
        - Transformer loss = 2%
- The lowest rated efficiency of the PCU is considered for calculations (96% for the current analysis).
- In most cases, the module degradation rate is considered as indicated in the manufacturer data sheet.

2.2 Considerations for Economic Model

The inputs to the financial model are based on the following assumptions:

- Capital-cost-related components are as follows:
    - Module cost = INR. 21/Wp
    - Land rate = INR. 5 lakhs/acre
    - Civil and general works = INR. 30 lakhs/MW
    - Preliminary and preoperative expenses = INR. 20 lakhs/MW
    - PCU = INR. 22 lakhs/MW
    - Ground mounting structures = INR. 30 lakhs/MW
    - Power evacuation infrastructure = INR. 40 lakhs/MW
- The Operations and Maintenance (O&M) expenses considered for the first year are INR. 7 lakhs/MW. The amount is then incremented annually by 5.72%. Miscellaneous expenses are considered at 5% of O&M expenses.
- Plant life is considered to be 25 years.
- The debt-equity ratio is taken as 70:30.
- The loan term period is considered to be 11 years, which includes a moratorium period of 1 year and a loan being serviced at an interest rate of 8.5% (the same interest rate is considered for the working capital component).
- The working capital consideration is as per CERC norms, considering the following components:
    - One month of O&M expenses, 15% of which is allotted for spares
    - Two months of receivables
    - 25% of the total working capital amount being considered as Margin Money for Working Capital (MMWC)
- The income tax rate considered is 30%, and the Minimum Alternate Tax (MAT) considered is 15% with a five-year rollover.
- The auxiliary consumption of the plant is considered to be 1% of the annual generation in year 1, and this is maintained constant for all years of operation.
- The book depreciation of assets is considered to be 5.83% for the duration of the term loan and is further allowed to be depreciated up to 90% by the end of plant life.
- The tax depreciation of assets per annum is considered as per the following norms:
    - Land at 0%. (Land value is not depreciated and hence not considered.)

- Buildings at 15%. This includes all aspects covered under civil and general costs.
- Plant and machinery at 50%. This includes all aspects covered under module costs, PCU costs and mounting structure costs.
- Other assets at 25%. This mainly includes evacuation infrastructure costs.

3. Sensitivity Analysis: Results

Based on the considerations indicated in the earlier chapter, we structure the estimated results across different locations (covered in section 3.1) in the following order:

- Resource estimation: This includes estimation of annual incident solar radiation on the tilted and the average cell temperature developed in the solar panel.
- Plant sizing: This includes the estimation of the number of modules in series and parallel combination, the number of inverters for supporting a target capacity. This will help in estimating the effective rating of the plant and the hence the area covered by the same.
- Plant output estimation: This includes estimation of the hourly plant output. We further extend this calculation to the life time of the plant factoring the effects of module degradation. This includes estimation of plant performance metrics
- Financial viability: Here we estimate the LCOE and other financial metrics of interest to assess the viability of the plant subject to technical estimations.

The above estimations serve as a base to perform two sensitivity analysis:

- The effect of module degradation on the financial viability of the plant (covered in section 3.2).
- The effect of cleaning cycles on the plant's LCOE (covered in section 3.3).

3.1 Climate-Zone-Wise Comparison

With the tilt angle and surface azimuth angle considerations, the annual incident useful solar radiation on the tilted panel (G_T) for all selected locations is presented in Figure 6[7]. We can see that Ladakh receives the highest total solar insolation among the four locations.

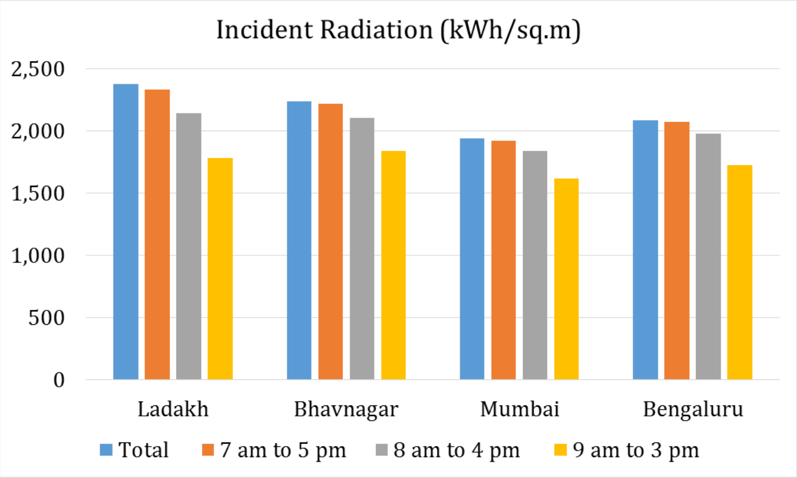

Figure 6: Annual incident solar radiation on a tilted panel

We estimate the cell temperature developed in each module because of the incident radiation, considering the ambient temperature and the effect of wind speed and present the results in

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[7] Here, module tilt is equal to the latitude of the location and orientation facing due south

Figure 8. We can see that apart from receiving the highest total solar radiation, Ladakh also has the lowest average cell temperature among the four locations.

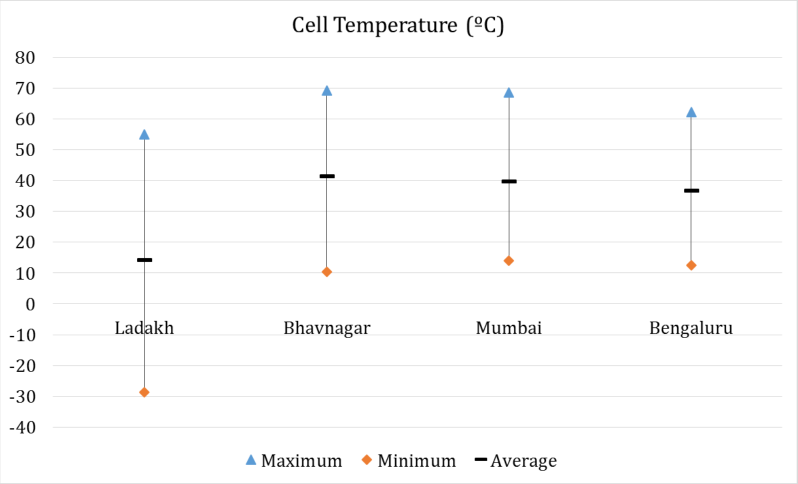

Figure 7: Cell temperature developed in the module

The PV plant is sized for a target capacity of 1 MWp, such that the maximum DC power generated by the array blocks involved is less than the PCU's power rating. Because of high incident solar radiation (in case of Ladakh, also low ambient temperatures) at Ladakh, Bhavnagar and Bengaluru, the plant capacities at these three locations have to be reduced from the original design capacity to adhere to the maximum DC power limit of the PCU. For the same reason, the capacity at Mumbai is slightly increased so that, under the best solar conditions, it can generate power close to the DC power limit of the PCU (indicated in Figure 9). Details of the plant design are indicated in Table 2.

Table 2: Plant design parameters (climate-zone-wise comparison)

	Ladakh	**Bhavnagar**	**Mumbai**	**Bengaluru**
No. of PCUs (N_{PCU})	4	4	4	4
No. of module strings in parallel per array (n)	2	4	4	6
No. of modules per string (m)	14	14	14	14
No. of arrays per PCU (y)	39	20	20	13
Total no. of modules in plant (N_{plant})	4,368	4,480	4,480	4,368
Plant capacity (P_{Plant}) in MWp	1.092	1.12	1.12	1.092
No. of module strings added/removed per PCU (Δm_{PCU})	-10	-8	5	-2
No. of panels added/removed from plant	-560	-448	280	-112
y per PCU for area estimation[8]	34	18	22	13
N_{plant} (limiting DC power)	3,808	4,032	4,760	4,256
Revised P_{Plant} in MWp	0.952	1.008	1.19	1.064

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[8] This refers to the final number of arrays (y) per inverter (PCU) for the area estimation.

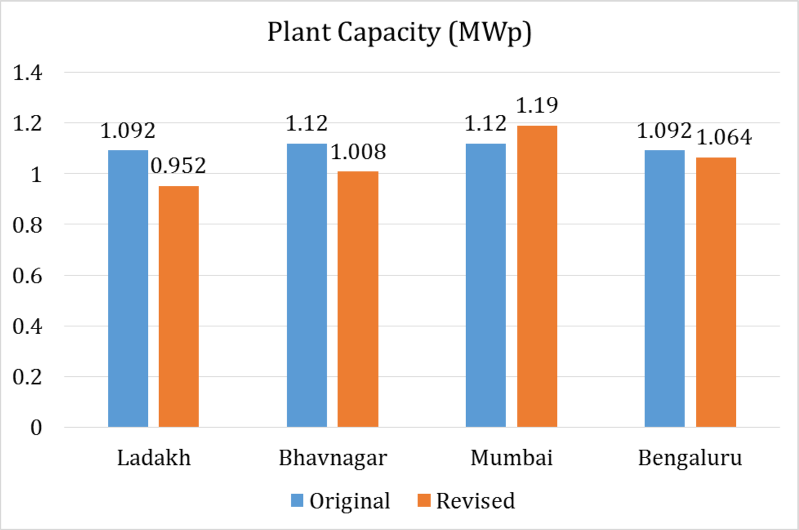

Figure 8: Location-wise original and revised plant capacity

We calculate the inter-row spacing (D_{row}) and the inter-column spacing (D_{col}) and indicate them in Figure 10 and Figure 11 respectively for a maximum array structure height of 2 m and considering the respective module tilts and orientations. Figure 12 indicates the total area covered by the modules alone. This translates to the active area effectively utilised for power conversion. We can see that this is in direct proportion to the effective plant capacity (MWp) considered for a given location. Ladakh has the lowest pure module area, while Mumbai has the highest.

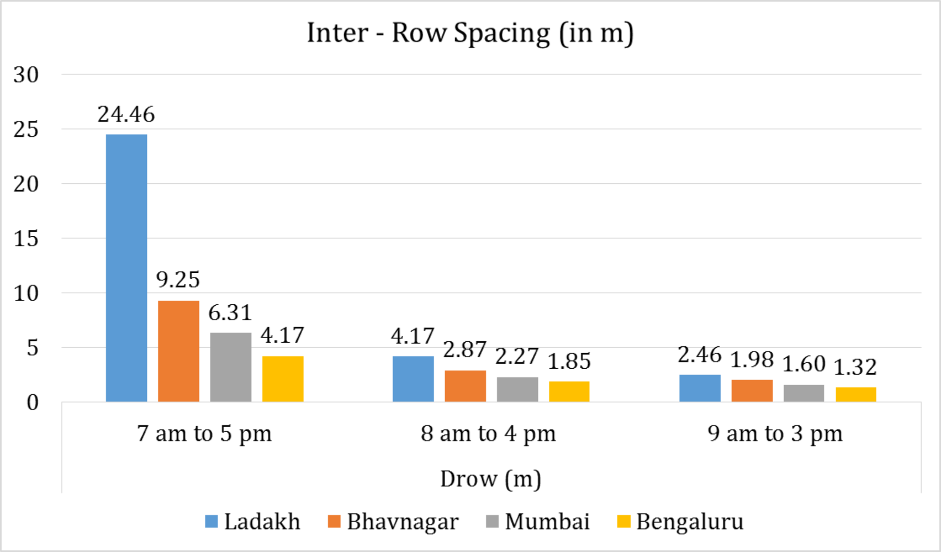

Figure 9: Inter-row spacing between arrays

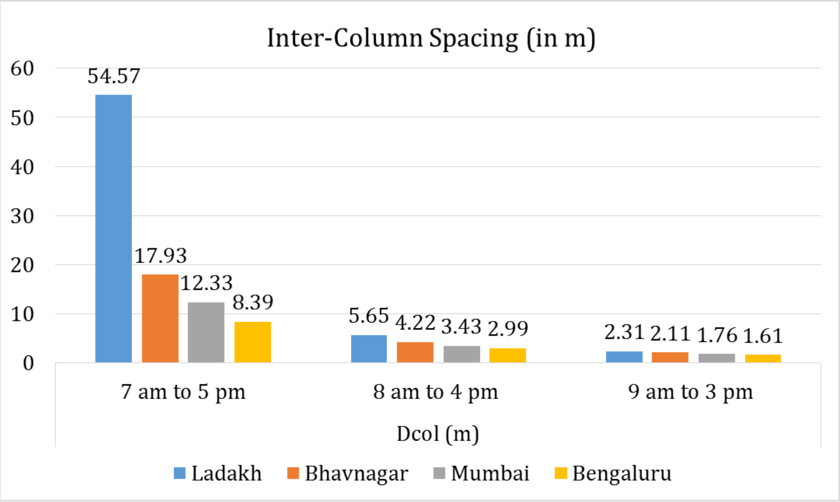

Figure 10: Inter-column spacing between arrays

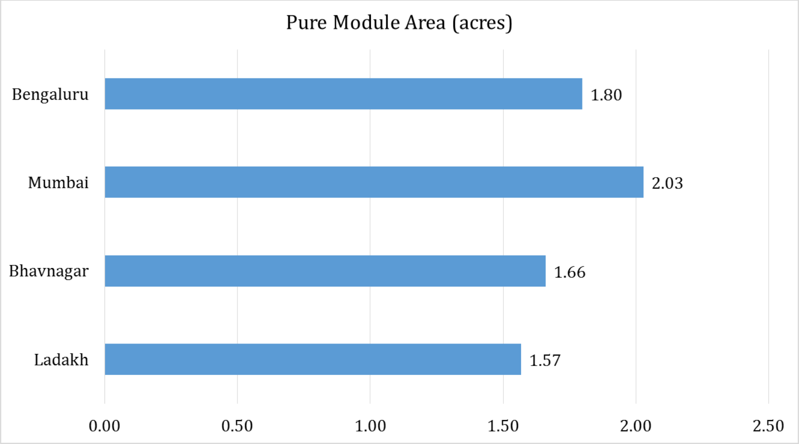

Figure 11: Area covered by the modules alone

Figure 13 indicates the total plant area requirements for the four chosen locations for different time windows. We can see that the inter-row and inter-column spacing requirements increase because of the steepening of the module tilt as latitude increases (indicated in Figure 10 and Figure 11, respectively). The corresponding plant area requirements for the given time window increase simultaneously. Now, we identify a suitable time window such that the absolute difference in area with respect to 5 acres/MWp, |Δ Area| (illustrated in Figure 14) is minimal. It can be seen that for all locations except Bengaluru, the minimal difference (highlighted in red) occurs for the time window of 8 am to 4 pm; for Bengaluru, however, this occurs from 7 am to 5 pm. (This is due to the lower tilt angle consideration for Bengaluru.)

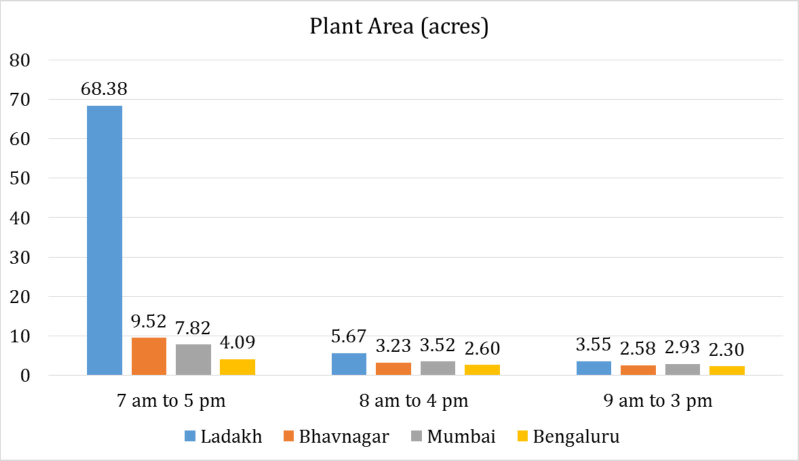

Figure 12: Estimated plant area for four locations

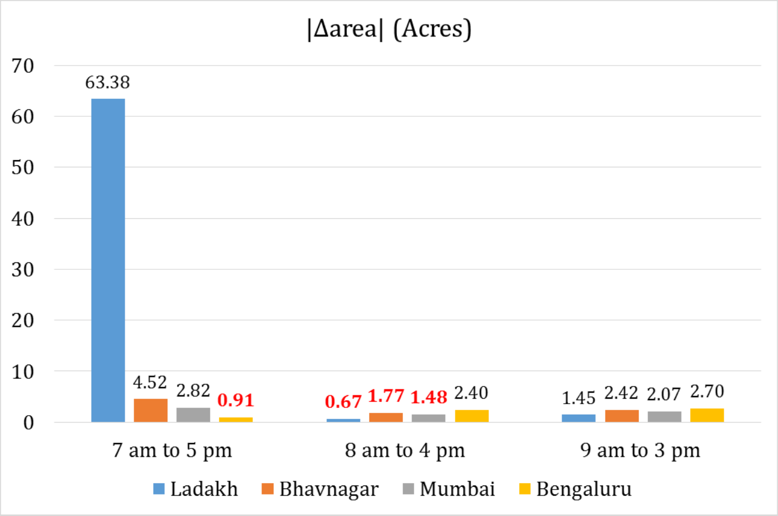

Figure 13: Estimated absolute difference in area w.r.t. benchmark area

Figure 15 and Figure 16 indicate the area-related performance metrics, namely, Ground Coverage Ratio (GCR) and Packing Density (PD)[9], for all locations across different time windows. We can see that GCR and PD increase with narrowing time windows because of the reduced plant area requirement. Because of the steeper tilt angle at higher latitudes, the GCR and PD for a given time window are always lower than the values at the corresponding lower-latitude locations.

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[9] Ground Coverage Ratio (GCR): It is defined as the array area divided by the ground area (covered by the tilted panel and the inter-row spacing).

Packing Density (PD): It is defined as the ratio of active module area to total plant area for a given time window and configuration.

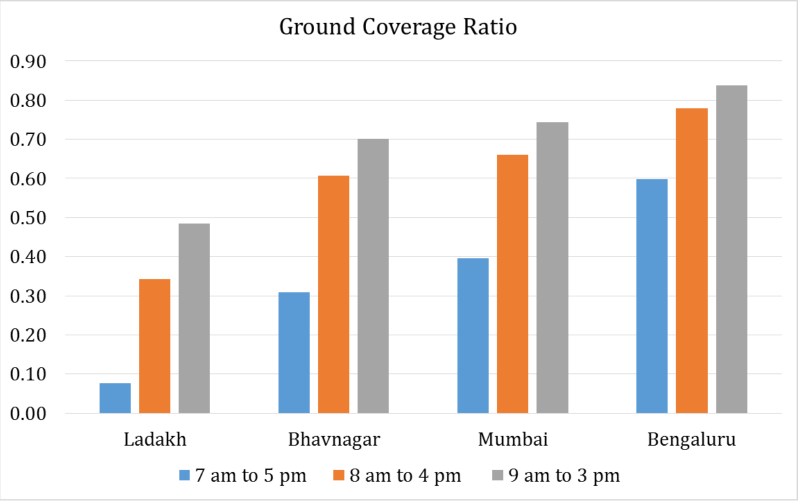

Figure 14: Ground coverage ratio

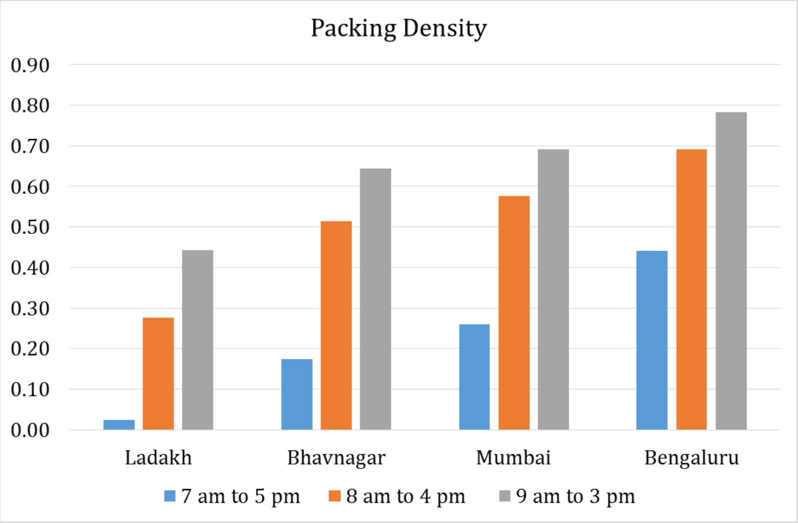

Figure 15: Packing density

Figure 17 illustrates the power generated by the designed plant for chosen time windows, considering no shading effects in the respective time windows and the maximum DC power limits of the PCU. Figure 18 indicates the power generation on a percentage basis with respect to the time window for a given location. From Figure 17[10], it may appear that Mumbai is a better location than Bhavnagar, because of the higher annual generation. This is, however, not true as the plant capacity in Mumbai is significantly higher than that at other locations. A better indicator of plant performance for the chosen time window of operation is the Performance Ratio (PR), which is indicated in Figure 19. We can see that the plant performance is the best in Ladakh.

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[10] Values indicated are the total for the chosen time windows - 8 am to 4 pm for Ladakh, Bhavnagar, Mumbai and 7 am to 5 pm for Bengaluru

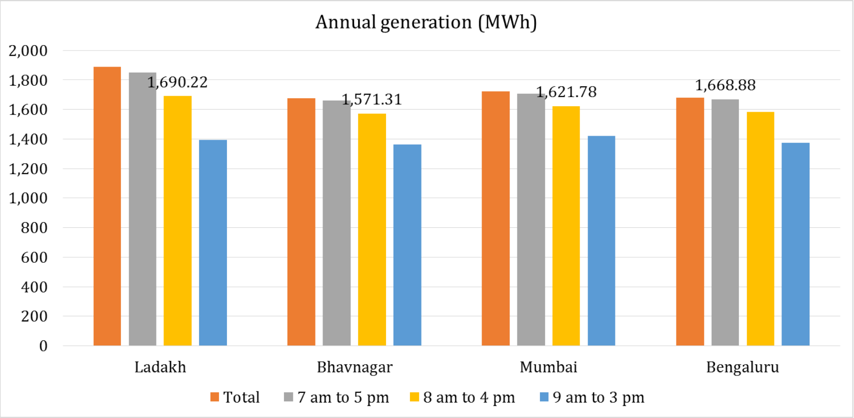

Figure 16: Annual solar energy generation

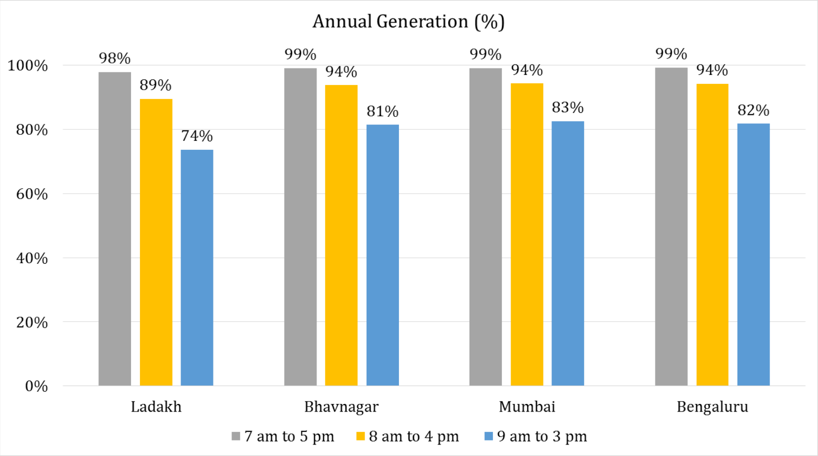

Figure 17: Annual solar energy generation as a percentage of total possible generation

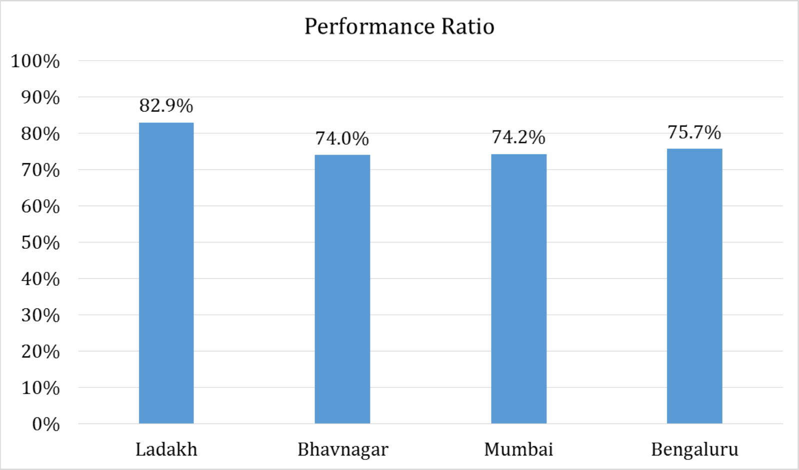

Figure 18: Performance ratios of plants for the chosen time window of operation

Figure 20 illustrates the frequency of generation from the simulated plants within their suitable time windows. In this figure, N indicates the percentage of generation with respect to the plant capacity. Despite its relatively small capacity, the plant at Ladakh has the highest number of hours in the category of 75% to 100% of the rated capacity. This is a testament to the favourable solar radiation and low ambient temperature in the location.

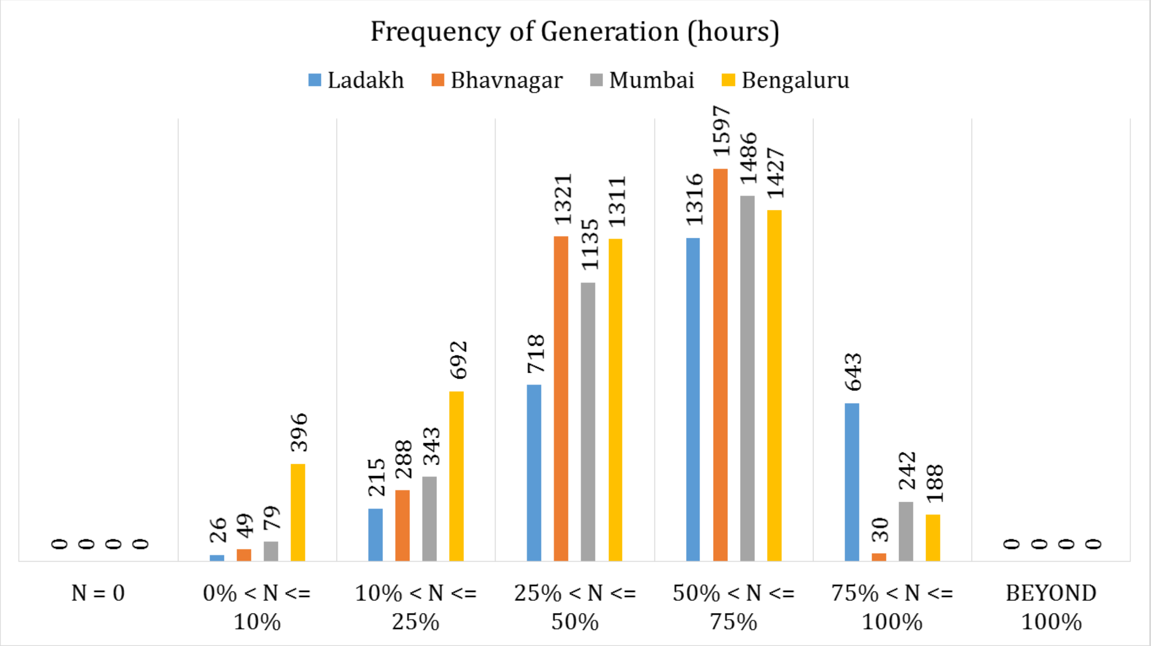

Figure 19: Spread of power generation for the chosen time windows

Module degradation is an important aspect that affects the techno-economics of solar PV plants. Figure 21 illustrates the annual power generation of plants at selected locations over their lifetimes, while accounting for module degradation.

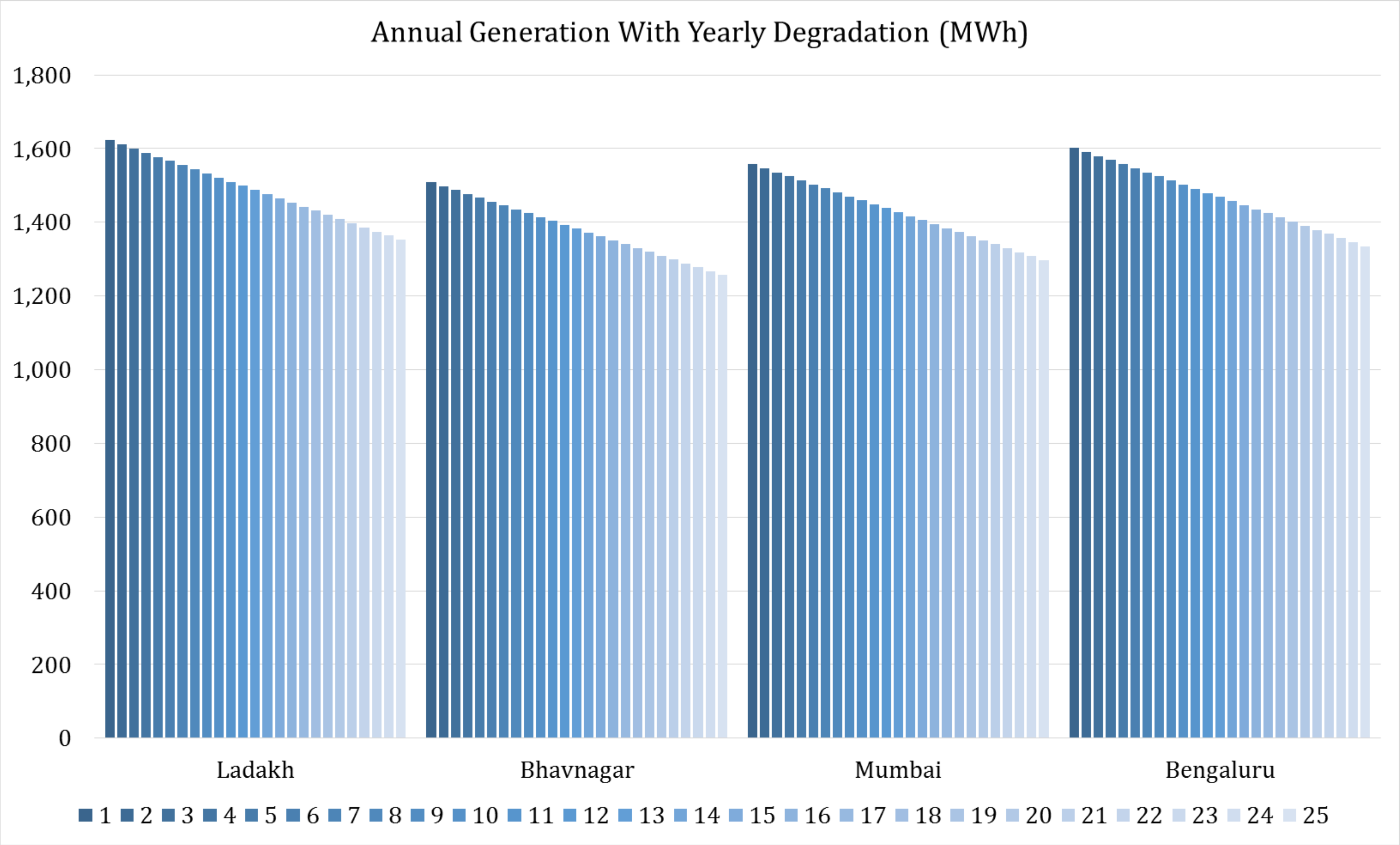

Figure 20: Annual generation of plants for the chosen time window factoring module degradation over lifetime (25 years)

As shown in Figure 22 and Figure 23, metrics such as Capacity Utilisation Factor (CUF) and Solar-to-Electric Efficiency (SEE) provide us a better way to capture the performance of the plants over their lifetimes[11]. Both CUF and SEE provide insights similar to PR.

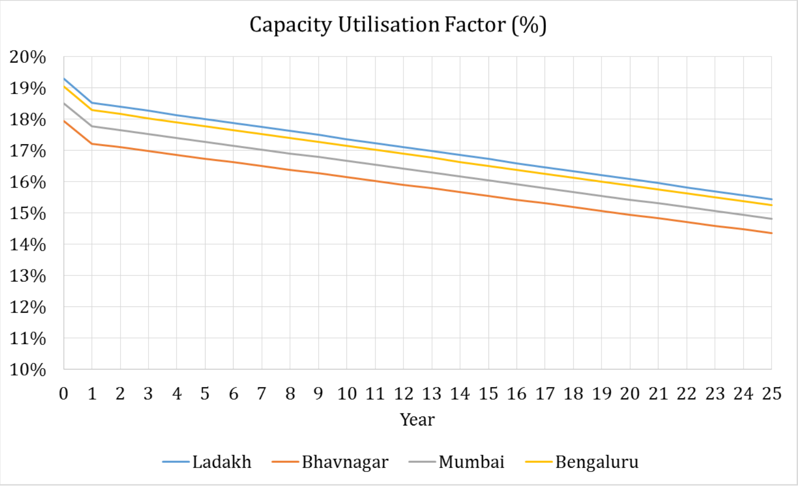

Figure 21: CUF of plants for the chosen time windows across lifetime

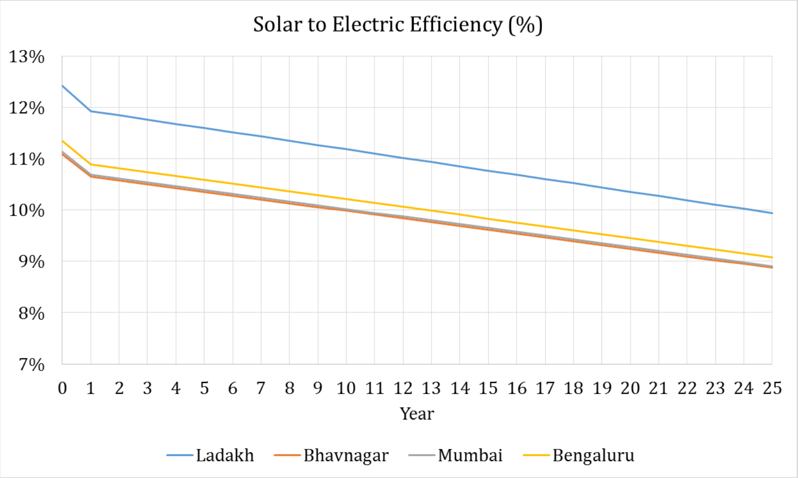

Figure 22: SEE of plants for the chosen time windows across lifetime

A crucial indicator of the techno-economics of a plant is the LCOE. Figure 24 depicts the LCOEs of the plants for the chosen time windows, considering module degradation. We can see that Ladakh offers the lowest LCOE. This is mainly because of the high solar radiation and low ambient temperatures at Ladakh. Although the plant has to be undersized to accommodate the maximum DC power limits of the PCU, this proves to be an advantage as it reduces the capital cost of the plant despite the higher land area required. Bhavnagar ranks second in terms of incident solar radiation. However, because of the narrower choice of time windows and the higher average ambient temperature at this location, the LCOE of the plant works out to be

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[11] It has to be noted that the general pattern of module degradation considers, drop of module rating to 97% by the end of year 1 and then following a linear module degradation at the rate of 0.67% per annum. It is due to this consideration, we observe a kink at the end of year 1.

almost equal to that in Bengaluru. The Mumbai plant has a higher annual generation, but reflects a higher LCOE because of the relatively poor solar radiation and, hence, an oversized plant capacity.

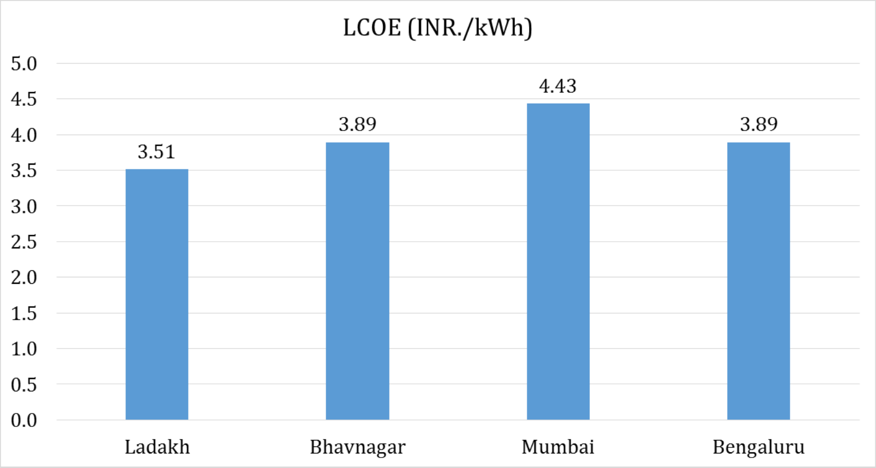

Figure 23: LCOE of plants for the chosen time windows

Figure 25 and Figure 26 respectively illustrate the trends of Earnings Before Interest Taxation Depreciation and Amortisation (EBITDA) and Profit After Tax (PAT)[12] over the lifetime of the plant when the solar tariff is set at the LCOE. Because EBITDA and PAT depend on the choice of solar tariff, their values follow the trend of the LCOE. Mumbai makes the highest EBITDA and PAT. This does not mean that Mumbai is the best location for setting up the plant. In fact, it has to be viewed from another perspective: Compared with other locations, Mumbai requires a higher tariff to sustain the same plant. The spike in PAT after year 11 is due to the completion of the loan term.

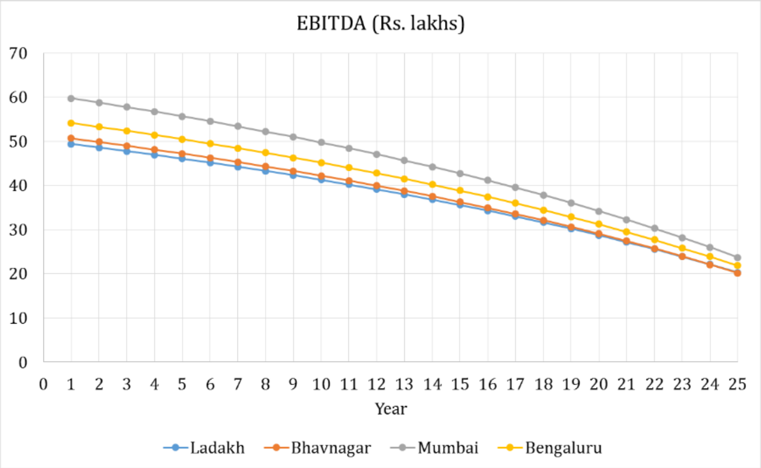

Figure 24: Trend of EBITDA of plants at LCOE over their lifetimes

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[12] For the scenario considered, the decreasing trend from year 8 to 9 is due to the tax amount being shifted from the Minimum Alternate Tax to effective Written Down Value. This leads to a slight increasing trend from Year 9 to Year 11. The spike observed in Year 12 is due to the end of the term loan and the change in the rate of annual depreciation.

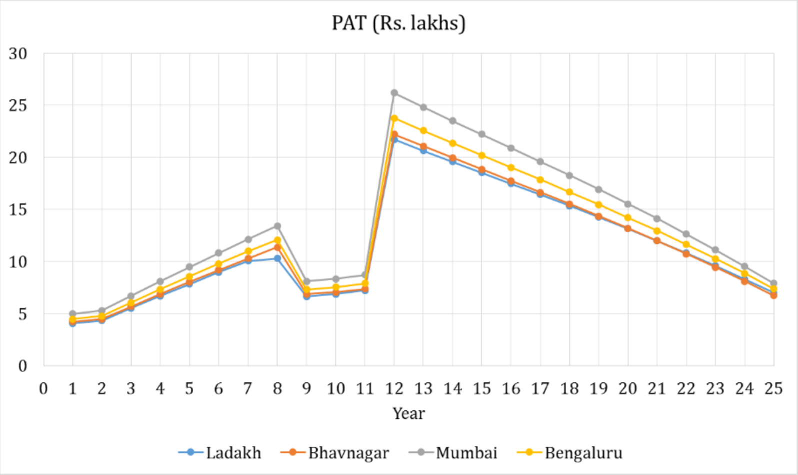

Figure 25: Trend of PAT of plants at LCOE over their lifetimes

3.2 Comparison of Degradation Rates

Module degradation rates significantly affect the techno-economics of solar PV plants. Specifically, the financial viability of a plant is at considerable risk if module degradation accelerates.

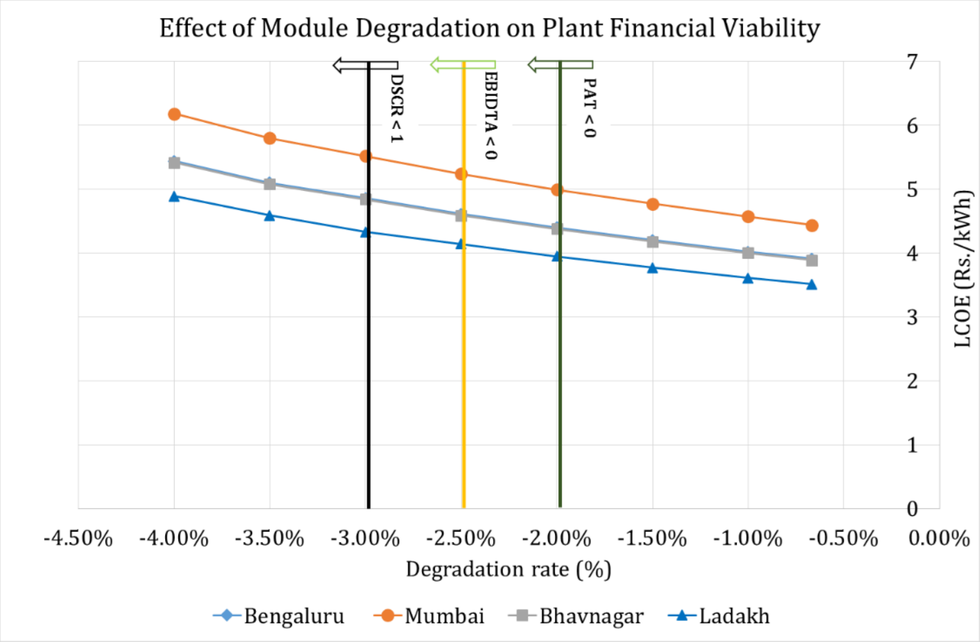

Figure 26: Effect of module degradation on the financial viability of plants

Figure 27 shows the change in LCOE for varying degradation rates of modules at a given location[13]. The critical degradation rates that mark important aspects regarding financial viability can be listed as follows:

- The rate beyond which PAT for at least one year is negative. This rate marks the point from which the plant is no longer profitable.
- The rate beyond which EBITDA for at least one year is negative. This rate marks the point from which the expenses of the plant can no longer be sustained.
- The rate beyond which the Debt Service Coverage Ratio (DSCR) for at least one year is less than 1. This rate marks the point from which the plant can no longer service its debt obligations.
- The maximum allowable degradation rate for a module is 4% per annum, considering the module would degrade to zero at the end of the plant life term (25 years). Beyond this rate, the plant is technically unviable over its prescribed lifetime.

Based on the technical performance and financial metrics of the plants simulated, Table 3 identifies these crucial degradation rates.

Table 3: Crucial degradation rates with respect to the financial viability of plants

Case	**Degradation Rate (%)**
Benchmark module annual degradation rate	0.67
PAT < 0 for at least one year; plant no longer profitable	>2
EBITDA < 0 for at least one year; plant can no longer sustain expenses	>2.5
DSCR < 1 for at least one year; plant can no longer service its debt obligations	>3
Plant is technically not viable within its lifetime	>4

3.3 Study on Effect of Soiling Losses – A Case for Mumbai

Soiling losses are energy losses that occur because of the accumulation of snow, dust, dirt and other particles on a module surface. Vehicle movement, wind-borne particles and other environmental and locational aspects result in the collection of dust. Such accumulation over prolonged periods can aggravate the loss due to soiling (Maghami et al., 2016). IIT Bombay indicated an approximate soiling loss estimate of 0.4% for the daily cleaning of modules in Mumbai. Further, it stated that for each day that was added to the cleaning cycle, the soiling loss increased in steps of 0.4% (John, 2015; NCPRE & NISE, 2016). Moreover, IIT Bombay (one of the research thrusts in SERIIUS) expressed an interest in understanding the effect of cleaning cycles on the LCOE of a plant. In this pursuit, CSTEP performed an analysis for a 1 MWp target plant in Mumbai for four variations in the cleaning cycle:

- Cleaning once a month
- Cleaning once every 15 days
- Cleaning once a week

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[13] Data for Bengaluru and Bhavnagar are similar, and hence they are superposed

- Cleaning every day

When considering cleaning once a month, the loss observed on successive days was considered from 0.4% to 12% in steps of 0.4%. A similar pattern was applied for the other cases. Considering the extreme cases of cleaning daily versus cleaning once a month, Figure 28 and Figure 29[14] show a comparison of daily soiling loss and daily plant output, respectively. We can see that the daily energy production in the two cases varies widely on some days but is quite similar on others. Also, the loss experienced by the system depends significantly on the energy generated by it, which is turn depends on the incident solar radiation and ambient conditions. To put this in perspective, the total annual DC plant energy output without soiling loss was estimated to be about 1,760 MWh. Table 4 lists the soiling loss estimate and hence the effective AC power output of the plant.

Figure 27: Comparison of daily soiling loss estimate for cases of cleaning once a month and every day

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[14] The modelling construct considered here takes a fixed soiling loss component during the entire period. The power estimation is done based on solar resource data indicated by the TMY file developed by NREL. The TMY file does not have precipitation data (NREL, 2015) and hence it was not possible to offset the soiling losses for the monsoon periods. In this regard the soiling loss calculated is a slight over-estimation.

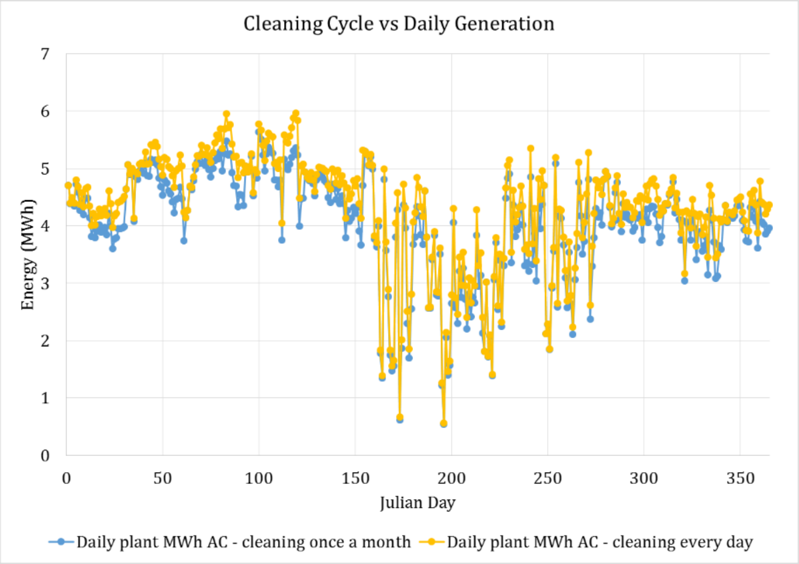

Figure 28: Comparison of daily AC outputs of power plants for cases of cleaning once a month and every day

Table 4: Summary of soiling loss and plant annual AC generation for different cleaning cycles

Case	Annual Soiling Loss (MWh)	Annual Plant AC Output (MWh)	Soiling Loss as a Percentage of Plant DC Output (%)
Cleaning once a month	105.81	1,478.06	6.01
Cleaning once in 15 days	53.37	1,524.93	3.03
Cleaning once in 7 days	25.68	1,549.68	1.46
Cleaning once a day	7.04	1,566.34	0.40

Using this effect of soiling loss as a basis, the LCOEs of the plants were estimated for different cleaning cycles (illustrated in Figure 30[15]), considering the decline in annual generation. *It could be seen that for each day of increase in the cleaning cycle, the LCOEs of the plants increase by around 1 paisa/kWh*. Figure 31 compares the monthly aggregate energy generation for a daily and a monthly cleaning cycle. We should keep in mind that the effect of soiling losses could be much higher in dusty regions.

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[15] The cleaning costs is included in the operation and maintenance (O&M) expenses. However, as per the data we received from the industry it did not have component wise breakup with respect to O&M. Hence we couldn't factor the increment/decrement of the cleaning costs.

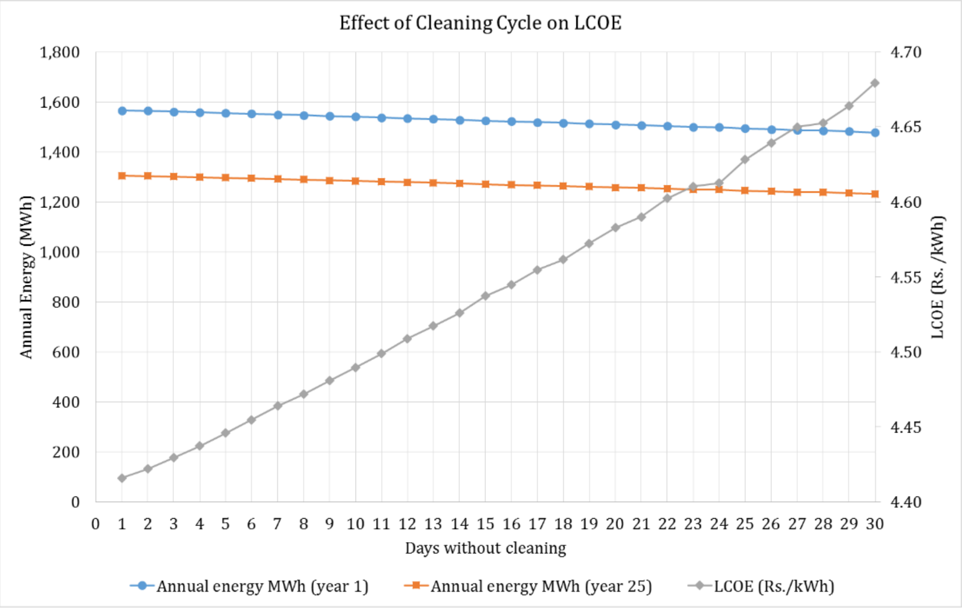

Figure 29: Effect of cleaning cycle on annual generation and LCOE

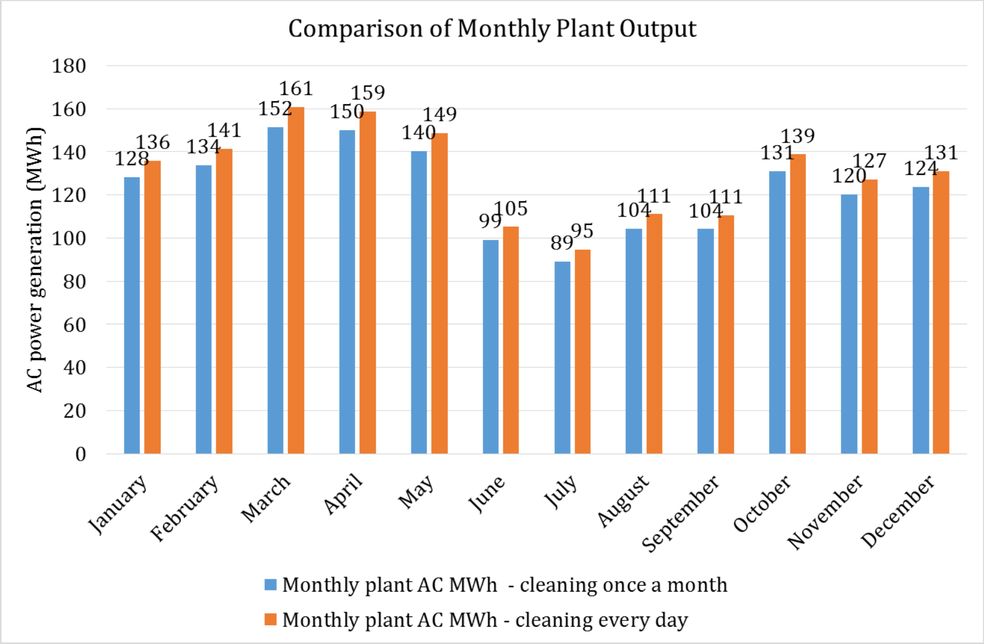

Figure 30: Effect of cleaning cycle on monthly aggregate generation

4. Summary

CSTEP conducted a study using the CSTEM PV tool to understand the effects of module degradation and soiling losses on a utility scale solar PV plants. The analysis considered the effect of latitude, module degradation due to soiling, cleaning cycle and time window of plant operation on the system performance from a techno-economic perspective.

The important aspects of the study are as presented below:

Generic Insights

The effect of standard module degradation on plant techno-economics for locations spread across different climate zones. The insights drawn from this are as follows:

- When considering the module tilt to be equal to the latitude of a location, the inter-row spacing and the inter-column spacing between panels increase on moving to higher latitudes. This results in an increase in the total plant area for a given time window.
- Annual energy generation is a function of solar radiation, ambient temperature, wind speed and the time window of operation for no shading conditions considered for the plant design.
- Plant area is a function of module dimensions, the time window of operation, the inter-row and inter-column spacing and the electrical configuration design after accounting for the maximum DC power limits of the PCU.
- LCOE is a prominent metric that captures the trade-off between technical and financial performance of the plant. EBITDA and PAT are functions of the solar tariff chosen for the plant and O&M, interest paid, depreciation and taxes.
- The decline of CUF and SEE follow the trend of year-on-year module degradation.

Impact of module degradation

A sensitivity analysis to identify the permissible level of annual module degradation rate such that the plant remains financially viable. Considering the case simulated for the plant, it was identified that

- The plant is not financially viable within its lifetime if the module degradation rate exceeds 4% p.a.
- The plant cannot meet its debt obligations if the degradation rate exceeds 3% p.a.
- The plant may not be profitable if the degradation rate exceeds 2% p.a.

Impact of soiling losses

The effect of the cleaning cycle on plant techno-economics (via soiling losses considering standard module degradation). For the case simulated (Mumbai), it was identified that for each day of increase in the cleaning cycle, the LCOEs of the plants increase by around 1 paisa/kWh.

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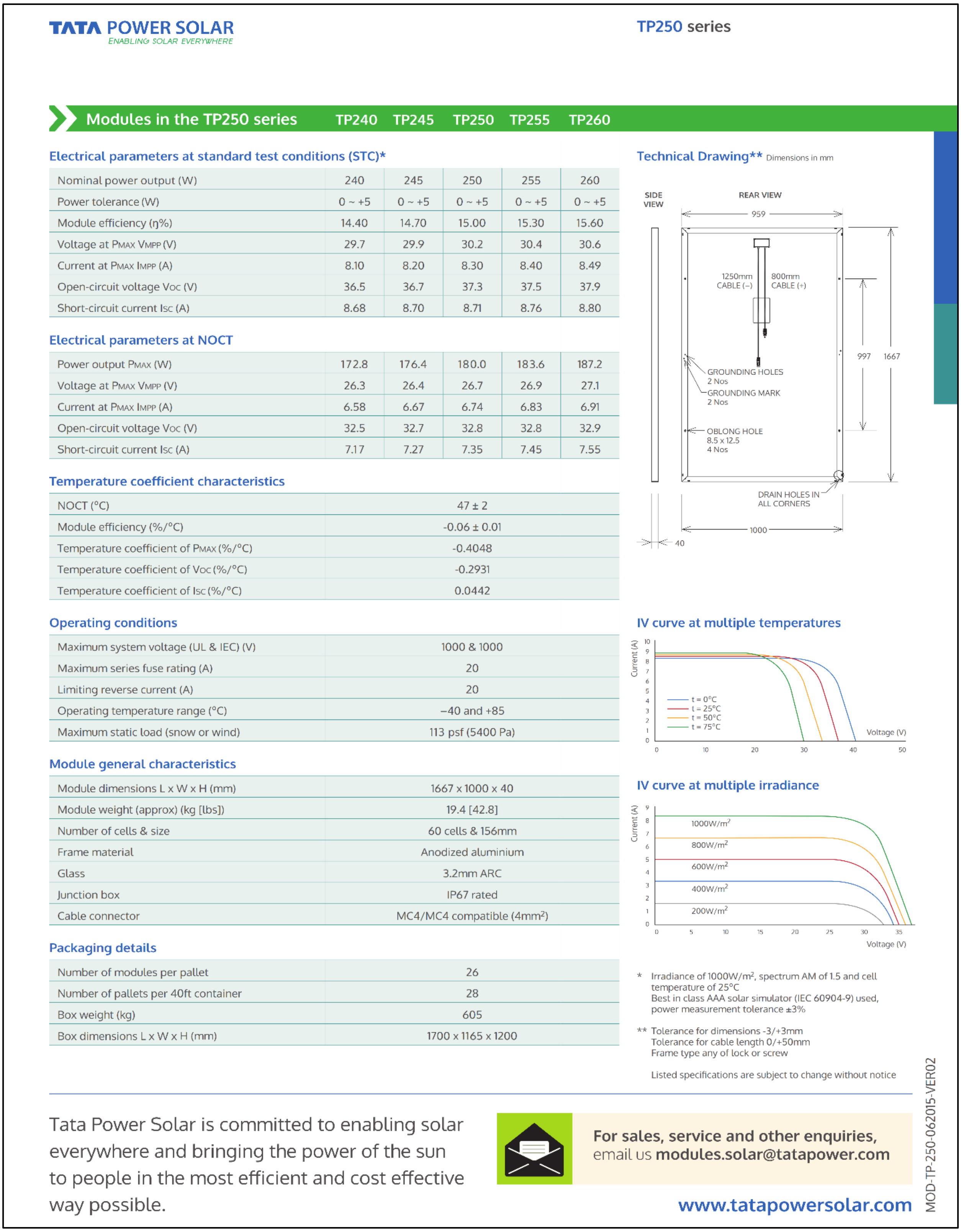
6. Appendix

Module Specifications[16]



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TP250 series

Modules in the TP250 series	TP240	TP245	TP250	TP255	TP260

Electrical parameters at standard test conditions (STC)*

Nominal power output (W)	240	245	250	255	260
Power tolerance (W)	0 ~ +5	0 ~ +5	0 ~ +5	0 ~ +5	0 ~ +5
Module efficiency (η%)	14.40	14.70	15.00	15.30	15.60
Voltage at PMAX VMPP (V)	29.7	29.9	30.2	30.4	30.6
Current at PMAX IMPP (A)	8.10	8.20	8.30	8.40	8.49
Open-circuit voltage Voc (V)	36.5	36.7	37.3	37.5	37.9
Short-circuit current Isc (A)	8.68	8.70	8.71	8.76	8.80

Electrical parameters at NOCT

Power output PMAX (W)	172.8	176.4	180.0	183.6	187.2
Voltage at PMAX VMPP (V)	26.3	26.4	26.7	26.9	27.1
Current at PMAX IMPP (A)	6.58	6.67	6.74	6.83	6.91
Open-circuit voltage Voc (V)	32.5	32.7	32.8	32.8	32.9
Short-circuit current Isc (A)	7.17	7.27	7.35	7.45	7.55

Temperature coefficient characteristics

NOCT (°C)	47 ± 2
Module efficiency (%/°C)	-0.06 ± 0.01
Temperature coefficient of PMAX (%/°C)	-0.4048
Temperature coefficient of Voc (%/°C)	-0.2931
Temperature coefficient of Isc (%/°C)	0.0442

Operating conditions

Maximum system voltage (UL & IEC) (V)	1000 & 1000
Maximum series fuse rating (A)	20
Limiting reverse current (A)	20
Operating temperature range (°C)	−40 and +85
Maximum static load (snow or wind)	113 psf (5400 Pa)

Module general characteristics

Module dimensions L x W x H (mm)	1667 x 1000 x 40
Module weight (approx) (kg [lbs])	19.4 [42.8]
Number of cells & size	60 cells & 156mm
Frame material	Anodized aluminium
Glass	3.2mm ARC
Junction box	IP67 rated
Cable connector	MC4/MC4 compatible (4mm²)

Packaging details

Number of modules per pallet	26
Number of pallets per 40ft container	28
Box weight (kg)	605
Box dimensions L x W x H (mm)	1700 x 1165 x 1200

Technical Drawing** Dimensions in mm

IV curve at multiple temperatures

IV curve at multiple irradiance

* Irradiance of 1000W/m², spectrum AM of 1.5 and cell temperature of 25°C
Best in class AAA solar simulator (IEC 60904-9) used, power measurement tolerance ±3%

** Tolerance for dimensions -3/+3mm
Tolerance for cable length 0/+50mm
Frame type any of lock or screw

Listed specifications are subject to change without notice

Tata Power Solar is committed to enabling solar everywhere and bringing the power of the sun to people in the most efficient and cost effective way possible.

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email us **modules.solar@tatapower.com**

www.tatapowersolar.com

MOD-TP-250-062015-VER02

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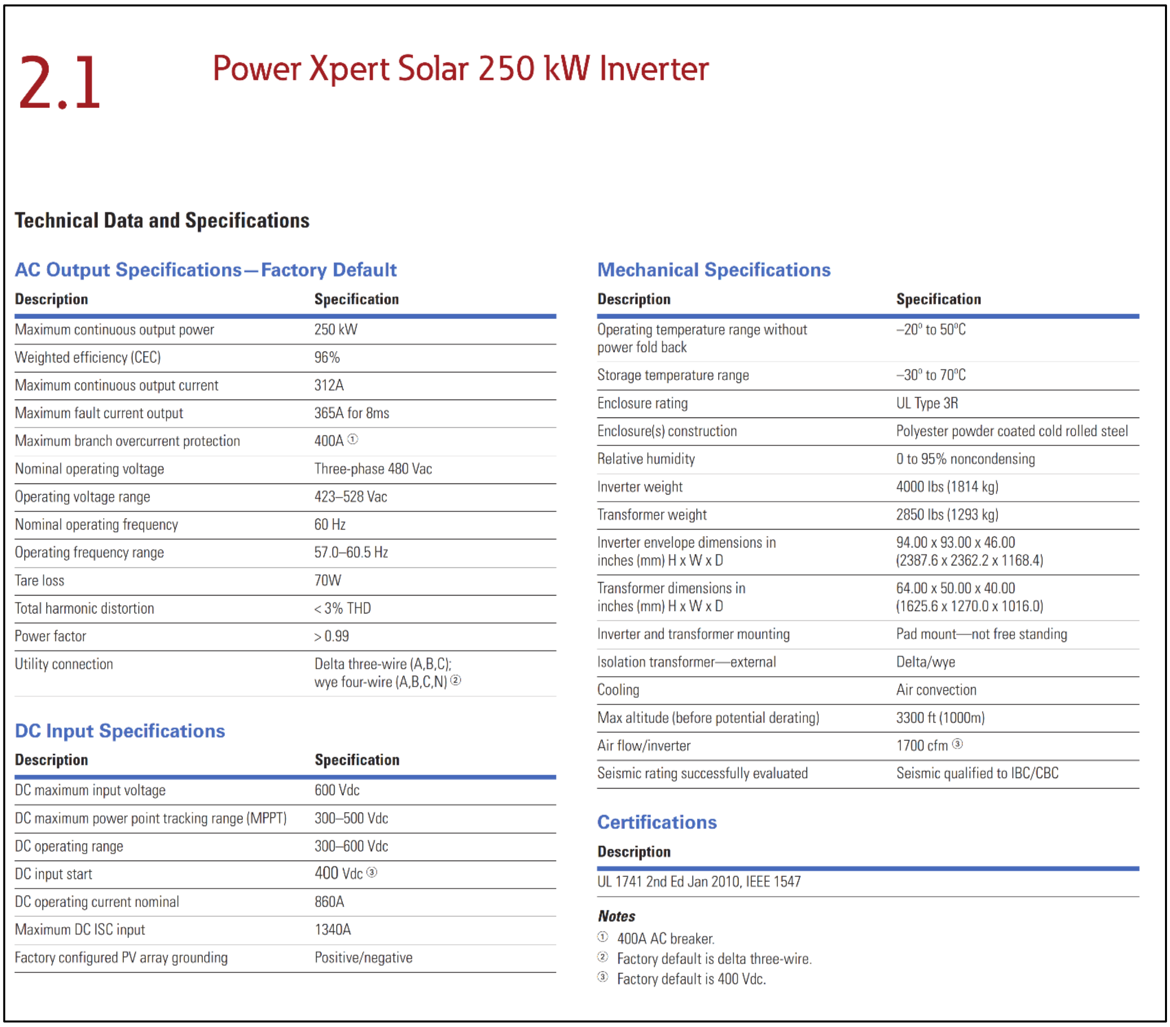
[16] http://www.tatapowersolar.com/images/module/downloads/20140422154949.pdf

Power Conditioning Unit / Inverter Specifications[17]



2.1

Power Xpert Solar 250 kW Inverter

Technical Data and Specifications

AC Output Specifications—Factory Default

Description	Specification
Maximum continuous output power	250 kW
Weighted efficiency (CEC)	96%
Maximum continuous output current	312A
Maximum fault current output	365A for 8ms
Maximum branch overcurrent protection	400A ①
Nominal operating voltage	Three-phase 480 Vac
Operating voltage range	423–528 Vac
Nominal operating frequency	60 Hz
Operating frequency range	57.0–60.5 Hz
Tare loss	70W
Total harmonic distortion	< 3% THD
Power factor	> 0.99
Utility connection	Delta three-wire (A,B,C); wye four-wire (A,B,C,N) ②

DC Input Specifications

Description	Specification
DC maximum input voltage	600 Vdc
DC maximum power point tracking range (MPPT)	300–500 Vdc
DC operating range	300–600 Vdc
DC input start	400 Vdc ③
DC operating current nominal	860A
Maximum DC ISC input	1340A
Factory configured PV array grounding	Positive/negative

Mechanical Specifications

Description	Specification
Operating temperature range without power fold back	–20° to 50°C
Storage temperature range	–30° to 70°C
Enclosure rating	UL Type 3R
Enclosure(s) construction	Polyester powder coated cold rolled steel
Relative humidity	0 to 95% noncondensing
Inverter weight	4000 lbs (1814 kg)
Transformer weight	2850 lbs (1293 kg)
Inverter envelope dimensions in inches (mm) H x W x D	94.00 x 93.00 x 46.00 (2387.6 x 2362.2 x 1168.4)
Transformer dimensions in inches (mm) H x W x D	64.00 x 50.00 x 40.00 (1625.6 x 1270.0 x 1016.0)
Inverter and transformer mounting	Pad mount—not free standing
Isolation transformer—external	Delta/wye
Cooling	Air convection
Max altitude (before potential derating)	3300 ft (1000m)
Air flow/inverter	1700 cfm ③
Seismic rating successfully evaluated	Seismic qualified to IBC/CBC

Certifications

Description
UL 1741 2nd Ed Jan 2010, IEEE 1547

Notes

① 400A AC breaker.
② Factory default is delta three-wire.
③ Factory default is 400 Vdc.

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[17] http://www.eaton.com/ecm/idcplg?IdcService=GET_FILE&allowInterrupt=1&RevisionSelectionMethod=LatestReleased&noSaveAs=0&Rendition=Primary&dDocName=PCT_402105

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