Pre-construction Solar Energy Yield Assessment

North American Validation Study

September 10, 2024

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Executive Summary

In the last few years, asset owners, asset managers, independent engineers and academics have reported underperformance across solar asset portfolios as compared with pre-construction P50 energy production estimates. Energy yield estimates are the cornerstone of project financial models, and the accuracy of these estimates is therefore imperative to understand. The industry must demonstrate continuous improvement and continue to develop an understanding of underlying issues behind energy yield prediction discrepancies. Natural Power has completed an audit of its current generation modeling methods and validated them against actual project performance.

Natural Power's validation study was split into two components: (1) a validation of pre-construction project modeling methods, and (2) an evaluation of solar project availability. This report presents both the results of the method validation study, which was based on 10 projects totaling 1.7 GWdc of capacity, and the availability evaluation, which was informed by 68 projects totaling 6 GWdc of capacity.

Results of both components of the validation study are presented below. The methods validation suggests that Natural Power's current methods for modeling performance produce accurate estimates with minimal bias (-0.2%). The availability assessment suggests that the median availability of a typical solar project is 98.2% and the average availability is 97.7%.

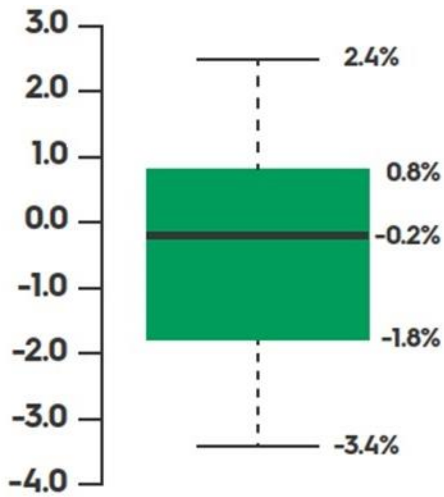

Figure 1.1: Percent difference between Natural Power pre-construction EYA and project performance[1]

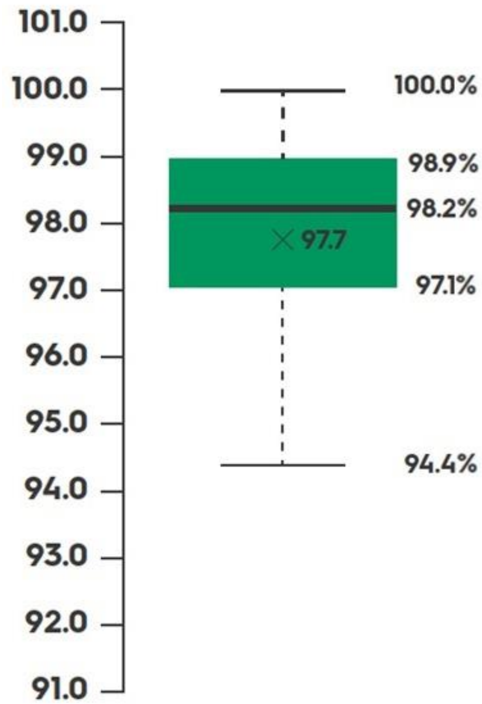

Figure 1.2: Solar project availability

[1] Negative numbers suggest that the pre-construction EYAs are underpredicting actual performance while positive numbers suggest an overprediction.

1. Introduction

A number of recent studies have reported underperformance across solar asset portfolios as compared with pre-construction P_{50}[2] energy production estimates.[3,4,5,6] A number of causes of overprediction bias in P_{50} estimates have recently been identified that had not been historically captured, notably sub-hourly clipping losses, terrain shading losses, wind-stow losses and overly aggressive estimates of solar project availability. The traditionally accepted availability assumption for solar projects in the US market is 99% which includes equipment as well as grid availability. Recent reports have shown that 99% is achievable, but not necessarily typical for solar projects.[7,8]

Natural Power has completed an audit of its current generation modeling methods and validated them against actual project performance. Natural Power's review was split into two components: (1) a methods validation that includes standard procedures for resource dataset selection, software and models, default assumptions and advanced modeling methods, and (2) a data-based assessment of achieved solar project availability.

[2] Fifty percent probability of exceedance (P50).

[3] Kharait et al. 2021 Solar Energy Assessment Validation for Utility Scale Projects. DNV-GL. 2022.

[4] Solar Risk Assessment 2022 and 2023. KWh Analytics.

[5] Bolinger et al. Plant-level performance and degradation of 31 GW-DC of utility-scale PV in the United States. LBNL. 2022.

[6] Jordan et al. PV field reliability status - Analysis of 100000 solar systems. NREL. 2020.

[7] ICF in the Solar Risk Assessment 2023. kWh Analytics.

[8] DNV, NREL and KWh Analytics in a DNV webinar - Are solar availability assumptions too optimistic?

2. Methods Validation

Natural Power evaluated the performance of a portfolio of 10 ground-mount solar projects totaling approximately 1.7 GWdc of capacity. The projects are spread across eight states, with capacities ranging from 20 MWdc to 200 MWdc, and commercial operation dates (CODs) ranging from 2016 to 2021. Collectively, the portfolio includes approximately 36 project-years of performance data. The portfolio includes seven operations and maintenance (O&M) contractors, eight engineering procurement and construction (EPC) contractors, five module suppliers, six inverter suppliers, four racking suppliers and four Independent Engineers (IE) of record. A summary of the portfolio is provided in Figure 2.1. The projects in the portfolio are a representative sample of typical utility-scale solar projects presently being built in North America.

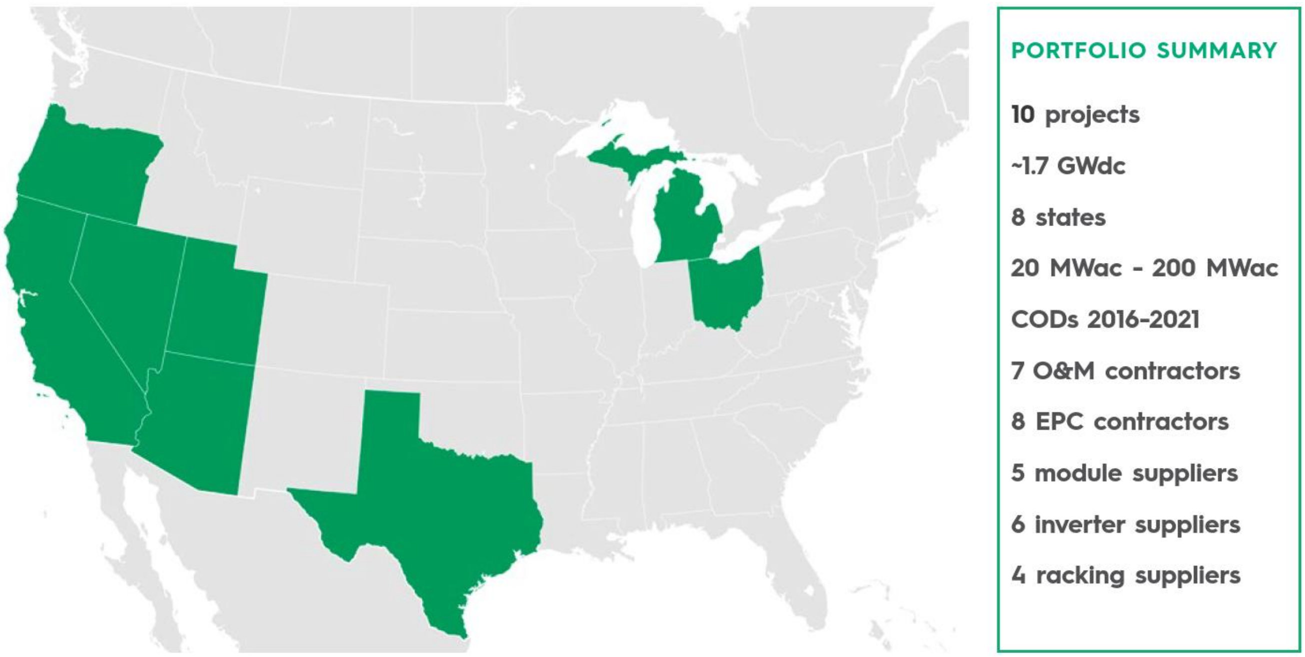

Figure 2.1: Portfolio summary

2.1. Pre-construction Energy Yield Assessments

As Natural Power was not the IE of record on these projects, Natural Power completed pre-construction energy yield assessments (EYAs) for each of the projects using current generation of modeling methods for solar projects. Though these are operational projects, Natural Power's analysis was limited to only data that is typically available at the pre-construction stage of a project. Natural Power's estimates included advanced modeling techniques for assessment of sub-hourly clipping losses, topography losses, and wind stow losses as described below.

2.1.1. Sub-hourly Clipping Losses

Sub-hourly clipping[9] loss refers to inverter clipping that occurs at the sub-hourly timescale. Solar projects are typically modeled at an hourly timescale, and it has been shown that hourly modeling can underestimate clipping losses for projects that have a high ratio of DC to AC capacity. Natural Power utilizes five-minute satellite-based irradiance data to model each project and assess sub-hourly clipping losses more accurately. A modeling correction is then applied to Natural Power's hourly energy estimates. In the sample of projects, these losses varied from 0.1%-1% based on the location and design of the project.

0.1-1.0%

2.1.2. Site Topography Losses

Ground undulation or site topography losses occur due to shading between rows of modules that aren't perfectly flat. Historically, solar projects have been built on relatively flat graded sites in the southwest and have been modeled as perfectly flat. Actual sites are not perfectly flat, which can increase the shading losses between rows, especially for tracker-based projects in complex terrain. Natural Power evaluates losses and gains associated with site specific topography. Typically, east, west and north facing slopes result in losses and south facing slopes result in gains. Natural Power acquires ground data from publicly available digital elevation models or grading plans for the project site and imports it into PVSyst. It was found that these losses varied significantly based on the terrain at the site and ranged from 0.5%-2% for the sample of projects.

0.5-2.0%

2.1.3. Wind Stow Losses

Tracker systems typically stow at their maximum tilt during high wind conditions to minimize damage. This can lead to production losses, especially in areas of high wind gusts. Natural Power calculates losses associated with tracker stow based on site specific historical wind data and the tracker supplier's wind stow strategy. In general, it was found these losses to be relatively small for the sample projects ranging from negligible to 0.5%.

0.0-0.5%

2.2. Operational Energy Yield Assessments

Comparing pre-construction EYAs with project performance can be challenging. An EYA is typically prepared for a P_{50} or typical year and is intended to be a median or average value. In actual operation, variables like irradiance, availability, and curtailment can fluctuate year to year, making it challenging to appropriately compare project production in a given year to the pre-construction EYA. To address this problem, Natural Power completed an operational energy yield assessment for each project.

Monthly production data from operating reports was correlated to a long-term irradiance dataset in order to derive an operational project performance model. The operational assessment includes an analysis of outliers in the production data, availability data and other directly measured losses (e.g. curtailment) compiled for each month from operational reports. Figure 2.2 shows an example of project performance correlated with irradiance. Gross yield has been adjusted to reflect 100% availability and 0% curtailment to improve the fit between production and irradiance.

[9] Clipping refers to the energy lost whenever the DC power of a solar system exceeds the AC capacity of the inverters.

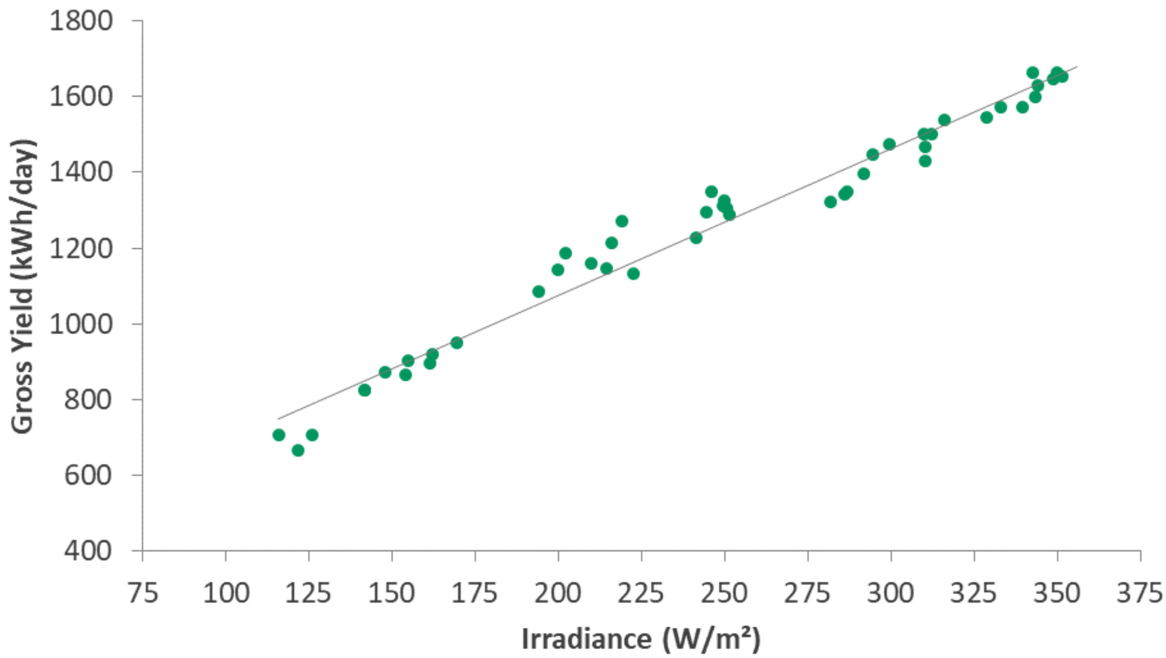

Figure 2.2: Example correlation between irradiance and project performance

A long-term average irradiance correction was carried out by applying the expected long-term average monthly irradiance to the project operational model to estimate long-term P_{50} energy production. This method allowed us to generate an energy estimate for an average or typical year, but that is based directly on historical project performance rather than a traditional pre-construction software model (e.g. PVsyst). Additionally, this estimate can be adjusted for availability, curtailment and long-term degradation so that it may be compared against the EYAs more accurately.

To ensure a direct comparison, the EYA and operational assessment were both adjusted to reflect long-term average irradiance conditions and adjusted to 100% availability and 0% curtailment losses. Long term system degradation of 0.5% per year was applied to the pre-construction EYA and the historical performance data for the operational assessment to ensure that both estimates were representative of the 2023 calendar year.

2.3. Results and Discussion

Figure 2.3 shows a box plot of the percent difference between Natural Power's EYA and operational assessment results. The box plot shows the minimum and maximum values, the lower quartile, median and upper quartile, and the whiskers show the range of values outside the interquartile range. Positive numbers in the figure indicate that the pre-construction EYA energy estimate is overpredicted, relative to the estimate based on historical project performance. A zero percent difference would mean that the EYA is in agreement with the operational assessment and perfectly representative of project performance (exclusive of availability and curtailment). The difference between Natural Power's EYA and operational assessment range from -3.4% to 2.4% with a median bias of -0.2% and an average bias of -0.4%.

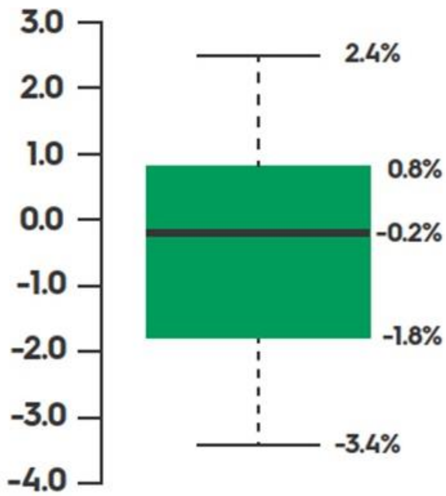

Figure 2.3: Percent difference between Natural Power EYA and project performance

The results show that there is good agreement between Natural Power's EYAs in comparison to observed project energy production, with a range in results. This range is likely reflective of uncertainty inherent in the methods used for typical EYAs and reporting of production, availability and curtailment losses. The results indicate that Natural Power's current generation of modeling methods are producing accurate results when compared with operational performance of projects. Natural Power notes that the comparison presented here is corrected for irradiance, thereby grossing out the impact of the irradiance dataset selection.

While the range of error in Natural Power's EYAs is well within the typical range of reported EYA uncertainties, there is still additional work to be done to further improve the validation process and to reduce the range of results. Natural Power expects to update this validation study on a regular basis by: 1) including projects from other geographical locations within the country, 2) further refining the advanced modeling methods used to minimize uncertainty, 3) evaluating the impact of the irradiance dataset selection process, and 4) assessing the process used to develop the uncertainty of pre-construction EYAs.

3. Availability Assessment

Natural Power evaluated the availability of a portfolio of 68 ground-mount solar projects totaling approximately 6 GWdc of capacity. The projects were spread across 22 states, with project capacities ranging from 20 MWdc to 300 MWdc, and CODs ranging from 2016 to 2021. The portfolio includes 11 O&M contractors, 14 EPC contractors, 10 module suppliers, 8 inverter suppliers, and 8 racking suppliers. Collectively the portfolio includes approximately 1,800 project-months of availability data. A summary of the portfolio is provided in Figure 3.1.

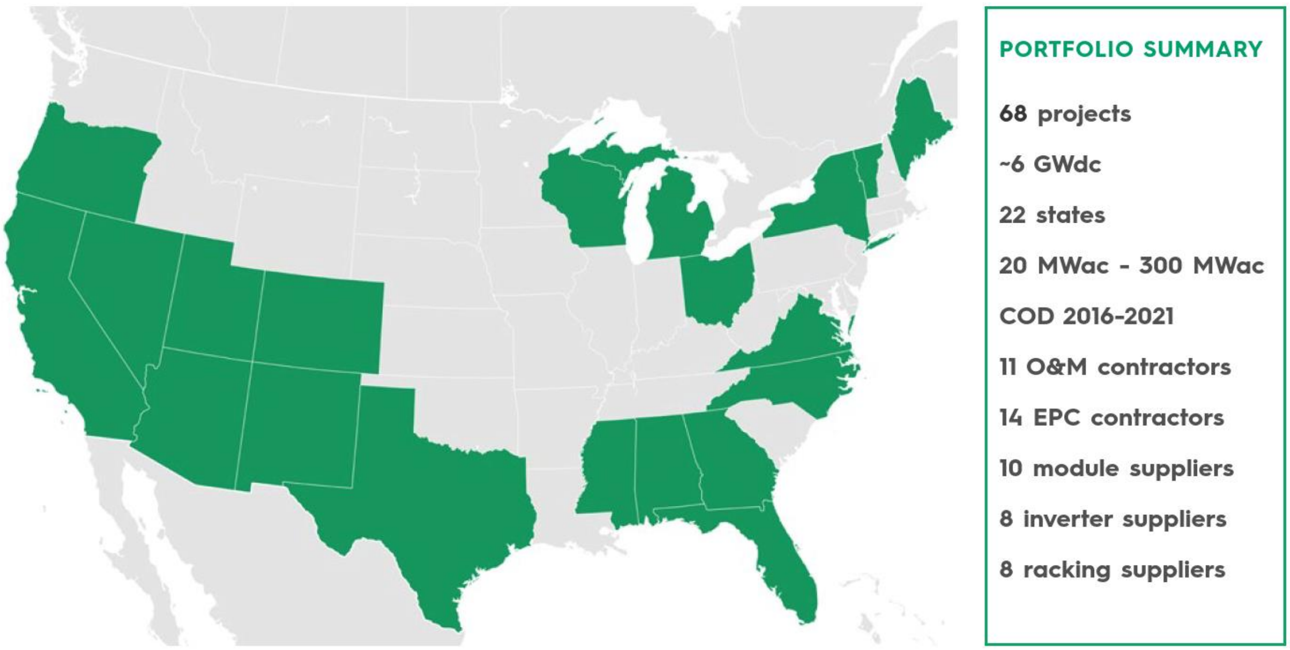

Figure 3.1: Portfolio summary

3.1. Methods

Solar projects are known to experience "teething issues" in the initial stages of operation which are not necessarily representative of long-term operation. As such, Natural Power excluded the first 6 months of availability data for each project from this analysis. A Monte Carlo simulation was used to randomly select 12 months at a time from the project-months of data available and generate 100,000 synthetic project-years. For example, a random January was selected from all Januarys available in the monthly dataset and so on for each month of the year. The availability of each synthetic project-year was averaged across the months in the year to produce 100,000 yearly availabilities. A Monte Carlo approach was used here as the dataset is limited to 1,800 project-months of data, which translates to approximately 150 project-years. As such, high or low outlier years could be biasing the results. A Monte Carlo simulation limits the impact of outliers and provides a better estimate of long-term availability trends.

3.2. Results and Discussion

The mean availability of each project-year was calculated, and the resulting distribution is presented in Figure 3.2. The distribution is non-normal primarily because the availability cannot exceed 100% but also because there were observed projects-years of production with significantly lower than typical availability which results in the long tail of the distribution. A Weibull curve provides a better distribution fit, which is consistent with Natural Power's expectations. The majority of project-years fall between 94.4% and 100%. The median availability is 98.2% and the mean is 97.7%. Additionally, the data shows that about 20-25% of the project-years fall above the "market standard" 99% availability.

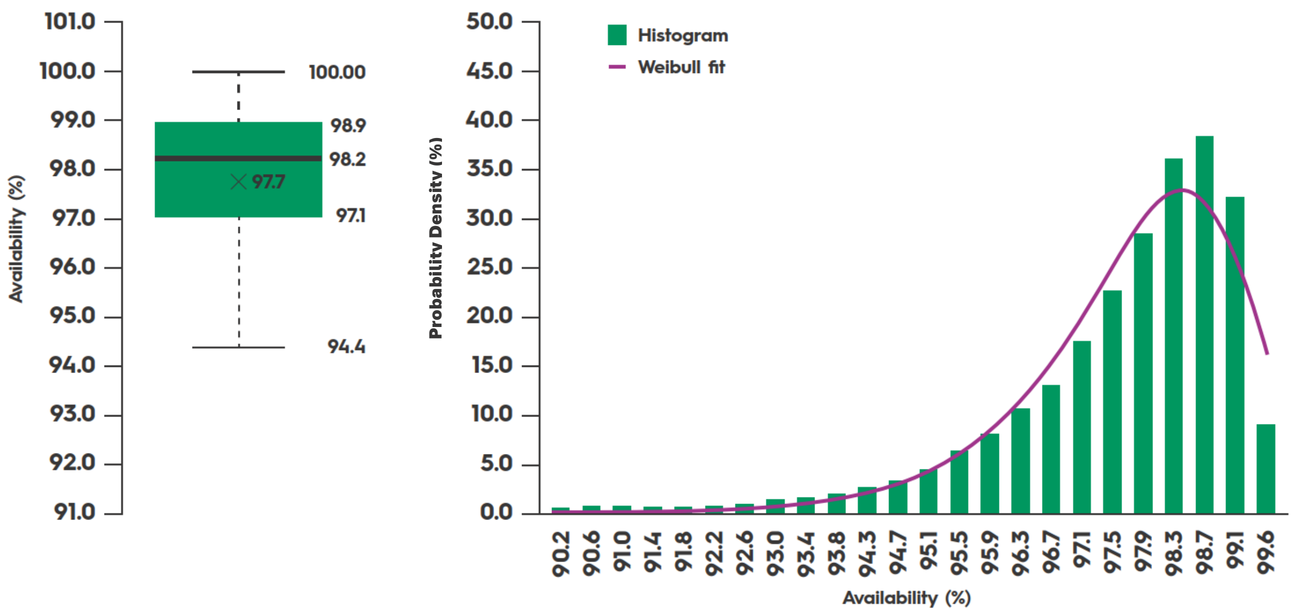

Figure 3.2: Availability distribution of synthetic project-years

3.2.1. Are "Teething Issues" Real?

First year "teething issues" have been anecdotally reported in the solar industry for multiple years. Figure 3.3 shows the average availability of the portfolio by operational month. The first month presented isn't a specific month in time, but rather the first month of each project's operation, which will vary based on when the project came online. There is a clear difference in availability in the first 6 months of operation vs subsequent months. The average in the first 6 months is 92%, while beyond that, there is variation from month to month, but the average is closer to 97-98%. Anecdotally, teething issues are sometimes reported to last for the first 1-2 years but that was not demonstrated in this dataset. In Natural Power's experience, the first 6 months of operation are often between substantial completion of the project and final completion. At substantial completion, the project is online and operational, but there is sometimes a punchlist that the EPC contractor is working through. The O&M contractor typically has not completely taken over operations so there can be some challenges due to a lack of clear ownership.

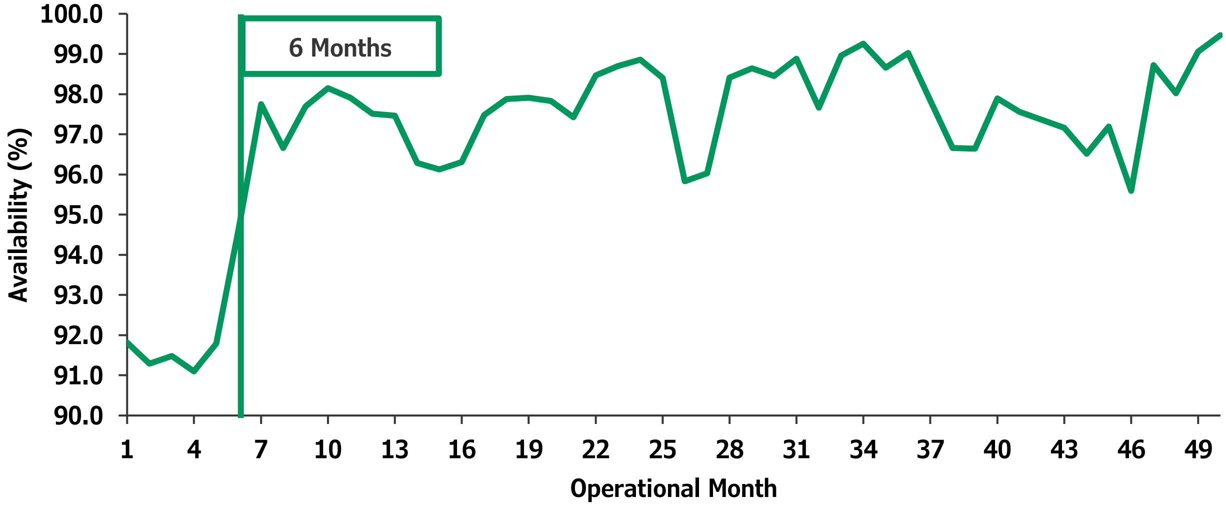

Figure 3.3: Average availability by operational month

3.2.2. Is Availability Getting Better or Worse with Time?

Natural Power reviewed the average availability across the portfolio as a function of year to estimate if the industry average availability is getting better or worse. As shown in Figure 3.4, the average availability of the portfolio has decreased from the 99% range in 2017-2019 to the 97% range in 2020-2022. Natural Power notes that the more recent years include significantly more project-months of data as more projects have been brought online.

There are a number of potential causes for this decrease in availability:

- **COVID and supply chain issues:** The solar supply chain in 2020-2022 experienced significant issues due to COVID lockdowns in multiple countries. This may have limited the availability of spare parts required to maintain a high availability.
- **O&M price pressures:** There is significant pressure on O&M contractors to minimize costs, which may be leading to lower availability.
- **New products rushed to market:** Inverter suppliers are also under pressure to reduce costs which may be leading to new products being rushed to market without appropriate testing.

While there are some data to suggest that the average availability is getting worse, the supply chain (and other) issues due to COVID have made it difficult to draw a reliable conclusion. At this time, it isn't clear if this is a temporary or permanent reduction in availability.

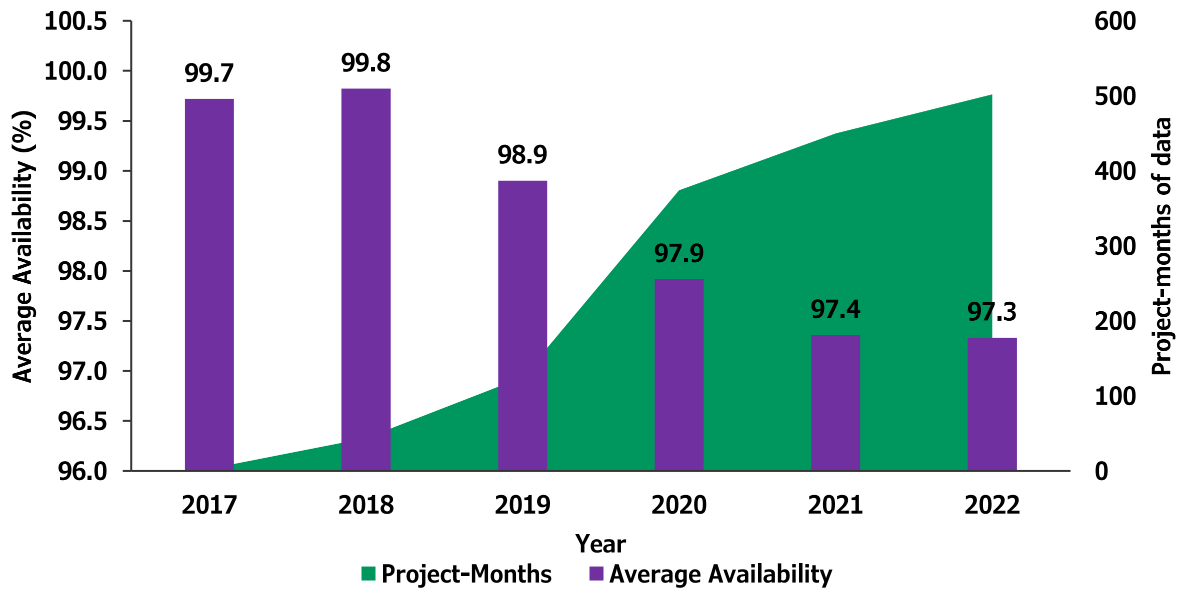

Figure 3.4: Average availability by year

3.2.3. Impact of Inverter Supplier

Inverters are often the primary cause of downtime in a solar project. Natural Power reviewed achieved availability across the portfolio of projects binned by inverter supplier. As shown in Figure 3.5, achieved availability for most suppliers ranges from 95% to 99%, with two suppliers achieving greater than 99% availability, on average. While there were some differences in availability between the "Tier 1"[10] suppliers with the most deployments, caution should be used when interpreting results binned by inverter supplier, as there are only on the order of 10 projects per supplier-bin for Tier 1 suppliers, and as few as a single project for others. Natural Power considers there to be insufficient data in the set to draw a conclusion about specific suppliers: availability can also be driven by other factors such as the original project construction, the O&M contractor and the asset manager, so the inverter supplier is only one driving factor.

The equipment supplier's experience providing products to the US market is an important factor in how the equipment will perform. Specifically, the equipment supplier should have a sizeable technical support team and appropriate warehousing for spare parts in the US, as these two factors determine how quickly failures can be addressed. Equipment that has a few years of field deployment data generally presents a more quantifiable failure risk than novel models of equipment. Natural Power recommends reviewing failure rates and/or warranty claim data for the individual models of equipment being deployed. However, the solar industry moves at a fast pace, and it is not always commercially viable to deploy equipment with many years of field data. For newer generations of product, Natural Power recommends evaluating the individual changes made from the previous generations of equipment to determine the degree of risk associated with the new product.

[10] "Tier 1" in this context is referring to the suppliers with the most central inverter shipments to the US market over the last five years. It is not intended to be representative of quality or reliability of these suppliers.

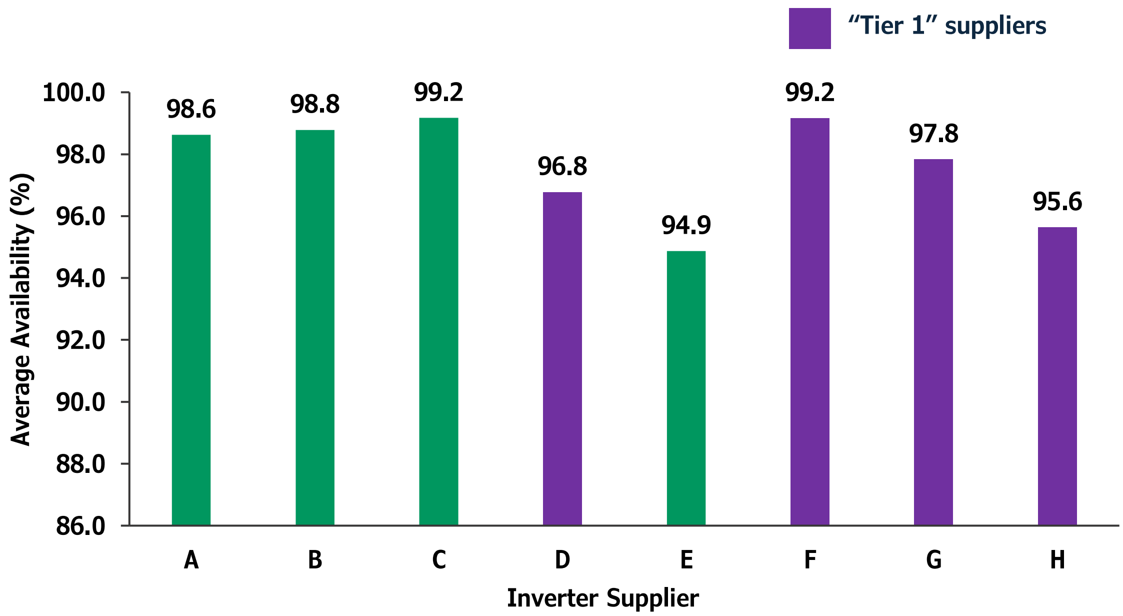

Figure 3.5: Average availability by inverter supplier

3.2.4. Impact of O&M Contractor

Another significant driver of availability is the O&M contractor's experience, the scope of services they have been contracted for, and degree to which the allotted budget allows for sufficient O&M activities. Figure 3.6 shows the average availability as a function of O&M contractor. The achieved availabilities range between 90.6% and 98.7%, but no contractor is able to achieve the typically assumed market standard 99.0% availability, on average. While there were some differences between O&M contractors, Natural Power considers there to be insufficient data in the set to draw a conclusion about specific contractors.

For projects that are focused on minimizing downtime, O&M contractor selection is critical. The O&M contractor should have significant experience with all equipment being deployed at the project. If the project is not staffed, they should have an appropriate presence of technicians in the project vicinity. Natural Power also recommends reviewing the O&M contractor's achieved historical availability for other similar projects in the area. The scope of services in the O&M agreement should include comprehensive monitoring of the project as well as preventative maintenance measures that are consistent with industry best practices and manufacturer recommendations. If corrective maintenance is excluded from the agreement, additional funds should be included in the O&M budget with an active asset manager that is able to approve O&M task orders in a timely manner. An availability guarantee with minimal exclusions and liquidated damages is also a benefit.

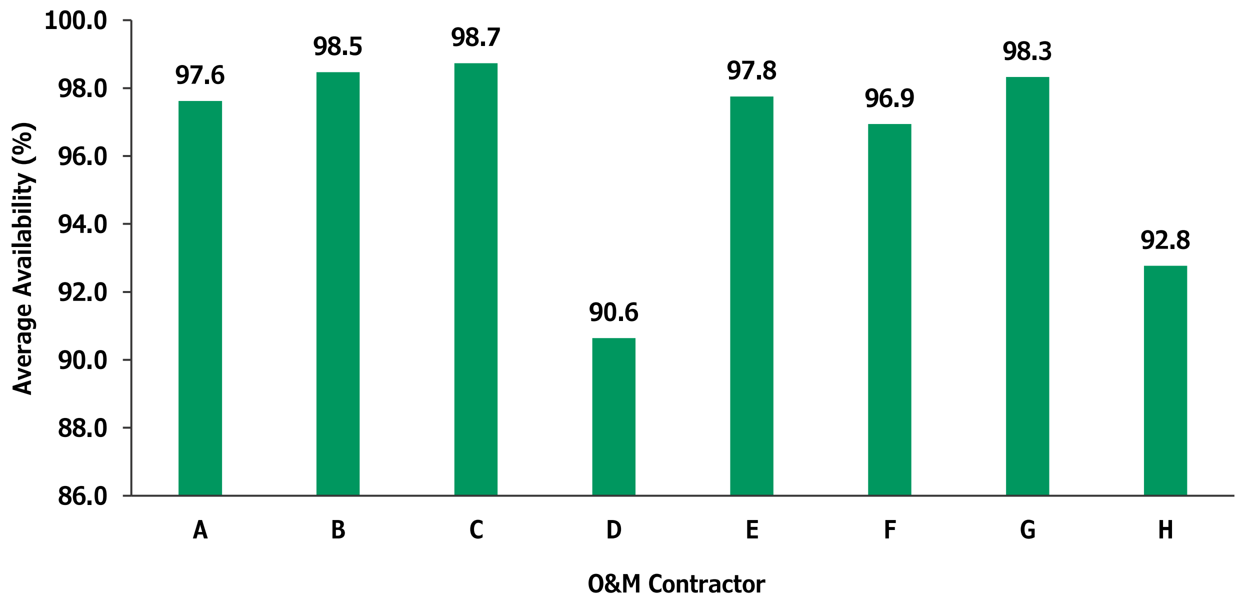

Figure 3.6: Average availability by O&M contractor

4. Conclusions

Natural Power has completed a validation of its current generation modeling methods and assumptions. Natural Power's review was split into two components: (1) a methods validation that includes standard procedures for resource dataset selection, software and models, default assumptions and advanced modeling methods, and (2) a data-based assessment of solar project availability.

4.1. Methods Validation

The methods validation included monthly performance, availability and curtailment data from 10 projects totaling approximately 1.7 GWdc of capacity. The projects were spread across eight states, with capacities ranging from 20 MWdc to 200 MWdc, and CODs ranging from 2016 to 2021. The dataset included multiple O&M contractors, EPC contractors, and equipment suppliers. The percent difference between Natural Power's pre-construction EYA energy estimates and actual observed production ranges from -3.4% to 2.4% with a median bias of -0.2%, indicating slight conservatism of the EYA estimates, exclusive of availability, curtailment and irradiance dataset selection. The results suggest that Natural Power's current generation of modeling methods that include losses for sub-hourly clipping, site topography and wind stow have minimal bias and a high degree of accuracy.

4.2. Availability Assessment

An availability audit was completed with monthly availability data from 68 projects totaling approximately 6 GWdc of capacity. The projects in the dataset were spread across 22 states, with capacities ranging from 20 MWdc to 300 MWdc, and CODs ranging from 2016 to 2021. The dataset included multiple O&M contractors, EPC contractors, and equipment suppliers. 1,800 project-months of availability data were used to generate the median yearly availability for 100,000 project-years. The results suggest that the "market standard" 99% availability assumption is achievable but not typical for most solar projects in the US market. The median project availability was 98.2% and the mean was 97.7%, with about 20-25% of the distribution falling above the "market standard" 99% availability assumption. When evaluating future project availability, Natural Power recommends considering the historical availability of the equipment to be deployed; the equipment supplier, O&M contractor and asset manager's experience; the O&M scope; and the overall O&M budget for the project.

Natural Power would like to emphasize that the analysis presented in this paper is focused on the US market, and different availability trends may apply in other regions such as Europe.

Creating a better environment

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