In-field performance of a polycrystalline versus a thin-film solar PV plant in Southeast Asia

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ABSTRACT

This paper considers the relative technical and economic performance, for selected sites in Southeast Asia, of PV plants using crystalline and thin-film PV module technology. Technical performance estimates are based on a forensic analysis of in-field data for two grid-connected PV installations in Thailand using polycrystalline and thin-film PV modules. These two case studies help to validate the performance simulation approach for the other considered countries with similar environmental conditions. The case studies show that Mott MacDonald's yield analysis approach demonstrates acceptable accuracy for energy yield assessment in a grid-connected PV plant, at least under the observed environmental conditions, which are most relevant to Southeast Asia plants with polycrystalline and thin-film PV modules installed. The findings presented in this paper are relevant to project developers and investors who have an interest in selecting solar PV technologies for Southeast Asian regional conditions.

Introduction

With over 102GW of cumulative global solar energy installed capacity at the end of 2012, crystalline silicon (c-Si) technology currently holds (and has so far always held) the world's largest market share of installed capacity of all PV module technologies [1]. The global market share of c-Si technology production is anticipated to maintain its position of at least 80% until 2017; this is primarily driven by continued rapid growth in installed solar PV plant capacity in Asia, particularly China and Japan, together with the competitively low production costs of c-Si technologies. Thin-film technologies have come off second best with around 14% market share of global production capacity in 2012, and are expected to grow at a lower rate than polycrystalline technologies until 2017 [1].

Significant drops in c-Si module prices (with a wide range of PV module quality, however) in the past few years [2], and c-Si technology's generally higher efficiency under standard test conditions (STC) compared with thin-film technologies, are undoubtedly two of the key influences contributing to polycrystalline PV modules' current domination of the market. Nonetheless, thin-film PV modules are commonly known as the 'better-performing' (i.e. higher specific yield) PV module technology under high-temperature and low-irradiance conditions, which are the two main factors determining any PV module's in-field performance and therefore the performance of the PV plant in question. One in-field operating data analysis in particular has shown that some thin-film technologies perform significantly better than c-Si modules in hot and humid climatic conditions [3]. Given that the PV module is the most significant single driver of plant performance, developers must carefully select a PV module technology to suit the designated climatic conditions of a PV plant while optimizing land area, in order to maximize project profit. With the above in mind, to optimize the PV project performance and profit, a number of other factors also need to be considered, including other key equipment, plant design, capital expenditure by technology, and climatic conditions.

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A great deal of constructive comparison of these two technologies is publicly available based on laboratory testing, an understanding of PV module fabrication, and the market price. That said, a fair comparison of plant performance for these two technologies cannot easily be given: a number of PV module performance features and plant design issues that significantly affect the overall performance of the PV plant are not adequately characterized by the PV module data sheet and standard laboratory tests.

Building on available generic comparisons of these two technologies, this paper initially provides case studies using high-resolution in-field data from two existing plants in Thailand (using polycrystalline and tandem-junction thin-film PV modules respectively) to validate the performance-modelling approach adopted. This validated approach will finally be further applied to gain more insight into how these two technologies perform at other regional site locations with similar climatic conditions.

This paper shares experiences and makes recommendations based on the different criteria that can be used to make a decision between using polycrystalline or thin-film PV modules.

Validation of PV plant performance modelling from in-field data

Before the relative performance of crystalline and thin-film plants is modelled, this section presents a validation, using in-field operating data from two case-study plants in Thailand, of the performance simulation method employed.

In-field operating data are mainly useful for understanding the performance characteristics of a PV module in an outdoor environment rather than its durability, because of the short-term nature of such available data from most PV module suppliers. Ideally, in-field data would exist from outdoor installations at independent test facilities, with more extensive performance monitoring and diagnostic capability than is customary at power plants. Such independent test

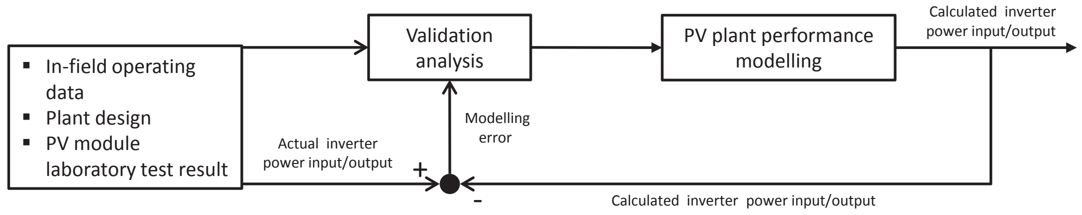


Figure 1. Methodology flow chart for PV plant performance-modelling validation.

Parameter	Unit	Resolution	Measuring device
Global horizontal irradiance	W/m²	1 minute	Horizontal pyranometer
Global inclined irradiance	W/m²	1 minute	Inclined pyranometer
Inverter input*	kW	1 minute	Inverter data logging device
Inverter output	kW	1 minute	Inverter data logging device
Ambient temperature	°C	1 minute	Ambient temperature sensor
Module temperature	°C	1 minute	Module temperature sensor

*Not available for Plant PC because of inadequate uncertainty level of the measurement device at the inverter

Table 1. Measured operating data for Plant PC and Plant TF.

facilities would usually have PV modules from a number of manufacturers, with these modules installed alongside each other for consistent comparison.

In cases where plant performance data are provided, in the authors' experience these have rarely been gathered and reported in accordance with recognized standards, so cannot always be taken as reliable and comparable without proper data quality checks. Another limitation of in-field data is that performance (and durability) evidence for one location with a given set of environmental conditions does not necessarily equate to similar performance at other locations.

This part of the paper focuses on a case study of seven days' available high-resolution in-field data, to gain more insight into the differences in PV module performance between polycrystalline and thin-film technologies, and to validate the adopted performance-modelling approach by the use of a combination of laboratory test data, plant design documentation and high-resolution in-field data from two existing plants (using polycrystalline and tandem-junction thin-film PV modules respectively).

The state-of-the-art software PVsyst (version 5.65) is widely considered an industry standard for solar PV plant performance simulation, and was used by Mott MacDonald in combination with other in-house models for this validation exercise. Since this analysis focuses on the difference in performance between two module technologies, the PV plant performance has been validated up to inverter level so that other unrelated losses (e.g. AC cable losses and transformer losses) can be disregarded. The simplified methodology flow chart of this analysis is illustrated in Fig. 1.

Overview of two utility-scale plants and their in-field data

The two projects in this analysis have been named 'Plant PC' and 'Plant TF' (for the purposes of confidentiality): they are in Thailand and use polycrystalline and thin-film PV modules respectively. The locations of the two solar PV plants analyzed are in northeastern and central Thailand, at latitudes between 14 and 15° N. A performance validation exercise for Plant PC specifically has been presented in a previous paper [4], which gives further details about the analytical approach adopted.

Table 1 shows the parameters that were used in this analysis over seven days. Mott MacDonald notes that not all of the provided parameters were used in this analysis, because of error, inconsistencies with other parameters, high uncertainties or inappropriate measurement principles, and are therefore not listed in Table 1. This operating data was quality-checked to help ensure that only reliable data were used for further analysis.

PV plant performance modelling up to inverter level

Losses were calculated on a one-minute basis using Mott MacDonald's in-house modelling, to give a more accurate prediction for the parameters dependent on actual irradiation and ambient temperature than would be possible using hourly time steps in PVsyst. In order to investigate the consistency of this approach, the in-house modelling used in this analysis is a higher-resolution reproduction of PVsyst modelling.

This analysis validates the PV plant performance modelling up to inverter input and inverter output levels for Plant PC and Plant TF respectively, given data availability. In this study the STC efficiency of the polycrystalline module used is 54% higher than that of the thin-film modules. A description of the approach and data used to estimate associated losses is given in Table 2.

Overall results

Based on the above validation approach, total calculated energy at the inverter level was compared with actual energy measured: the results are shown in Table 3. Total calculated energy delivered at the inverter input and output levels, after data screening, is 99.40% and 100.86% of total actual inverter energy measured at Plant PC and Plant TF respectively. These differences are within the margin of error of the metering equipment (±3% for AC inverter power measurements, ±2% daily for irradiance).

Taken together with the high correlation coefficient between calculated and actual inverter power input and output on a one-minute basis, the results of this analysis demonstrate good agreement between Mott MacDonald's in-house modelling and

Type of loss	Source	Approach
Spectral	PVsyst	Based on the sun angle profile computed in PVsyst, Mott MacDonald has calculated irradiance-weighted average air mass (AM) per kWh for the period observed close to the STC condition of AM1.5. Spectral losses have therefore been neglected in this analysis.
Shading	PVsyst	Hourly shading loss profile from PVsyst was applied in this 1-minute analysis over 7 days using a linear interpolation approach.
Angular	PVsyst and module supplier	Hourly angular loss profile of PV module observed from PVsyst was applied in this 1-minute analysis over the period observed using a linear interpolation approach.
Low-irradiance performance	Module supplier	The low-irradiance test data provided for the module supplier was used to calculate low-irradiance loss on a 1-minute basis. Expected degradation has also been taken into account in the PV module's efficiency in all irradiance conditions.
Temperature losses	PVsyst	Actual module temperatures are used together with the rated 'temperature coefficient of P_{max}' for the PV module. While this calculation of temperature loss is a simpler linear approach than that with PVsyst, there are, in this case, negligible differences in the result of this calculation step. PVsyst does not allow module temperatures to be directly input, but instead calculates cell temperature from ambient temperature and irradiance, which can result in errors. Given that operating data are available, Mott MacDonald's in-house simulation uses actual module temperature data and provides results that are more consistent with actual performance data than if the PVsyst approach were used.
Power tolerance	Module supplier	PV module flash test results for both plants have shown a positive average tolerance (gain).
Mismatch	Module supplier	Flash test results of the delivered PV modules used in the plant and string configuration data, together with Mott MacDonald's in-house analysis, were used to calculate average mismatch losses.
Ohmic, DC	Plant design	DC loss or I^2R loss has been calculated based on the given cable size and lengths from the modules to the inverters.
MPPT performance	Weather	Because of the clear-sky operating data received and the inverter characteristics, the MPPT (maximum power point tracking) performance loss has been considered negligible over this period, since the maximum power point of each array remains relatively stable.
AC/DC conversion performance*	Inverter supplier and PVsyst	AC/DC performance loss has been calculated from the inverter performance curve in the PVsyst library, corroborated against the supplier data sheet.
Dust	Module-cleaning schedule	In accordance with the module-cleaning schedule, the modules at both plants were cleaned immediately before the observation period. For Plant PC, dust/soiling loss was assumed to be negligible in this analysis. For Plant TF, the observation period was affected by significant soiling due to on-going construction at a nearby site. A nominal average soiling loss of 1.28% was determined from an additional analysis and was derived from calculated module power output at the STC condition.
Availability	Operating data	On the basis of the operating data, availability has been estimated at 100% over the observation period.

*Only used for Plant PC to validate the plant performance at inverter output level

Table 2. Treatment of losses at Plant PC and Plant TF in plant performance modelling.

Power Generation

actual plant performance for the specific losses considered under the observed environmental conditions for both plants.

> "The results of this analysis demonstrate good agreement between Mott MacDonald's in-house modelling and actual plant performance for the specific losses considered."

Performance comparison of polycrystalline and thin-film technologies

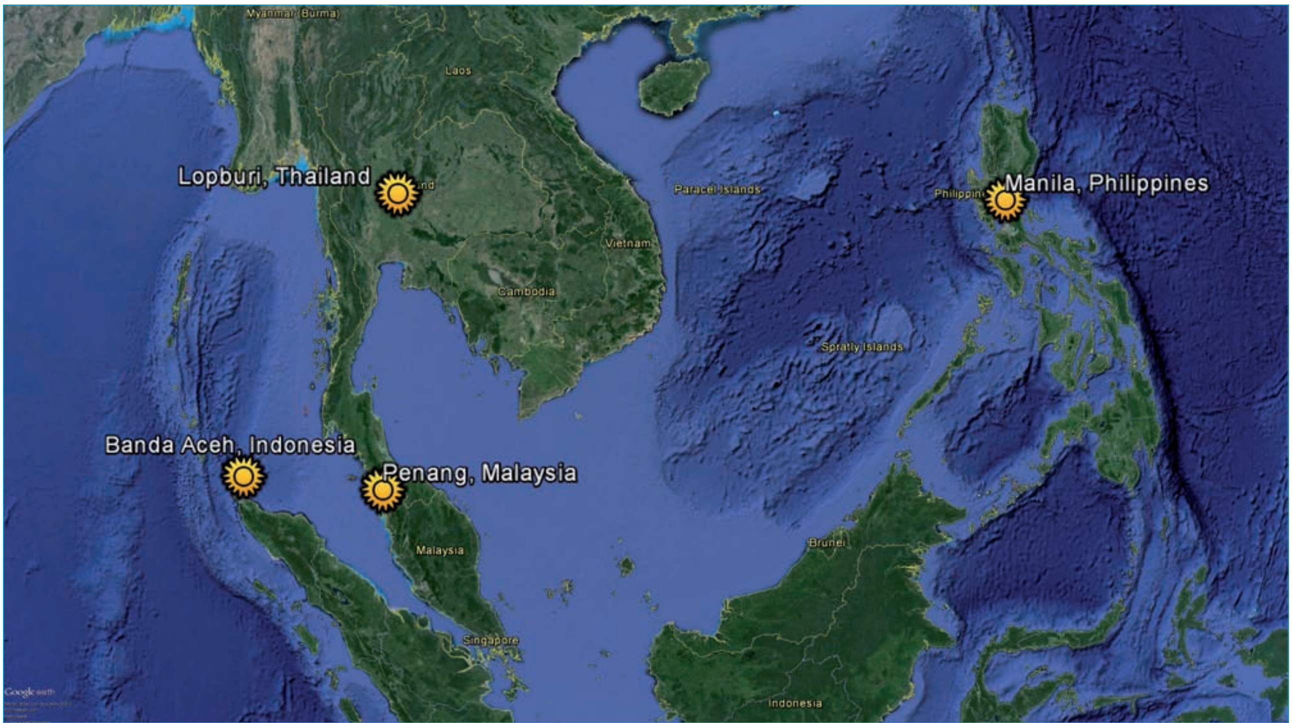
On the basis of the validated PV plant performance modelling discussed above, this section compares the performance of polycrystalline and thin-film technologies at other regional site locations with similar climatic conditions. Since the two specific PV modules (polycrystalline and thin-film) from the validation analysis have been proved to show good agreement with actual outcomes, these two modules were also chosen for this comparison exercise.

Thailand, Malaysia, Indonesia and the Philippines were selected for this comparison exercise because of their potential PV market sector growth [5]. Each location in these countries was nominated by an area with a known high global horizontal irradiation (GHI) resource for the respective country, with reference to public domain data.

The four tropical locations chosen for the comparison are indicated in Fig. 2, with their respective annual GHIs and ambient temperatures shown in Table 4.

	Calculated energy compared with actual energy		Correlation coefficient
	measured at inverter input	measured at inverter output	
Plant PC	-	99.40%	99.49%
Plant TF	100.86%	-	99.93%

Table 3. Comparison of calculated and actual energy at inverter level for Plant PC and Plant TF.



Source: Google Earth 2013

Figure 2. Selected locations for the comparison exercise.

	Lopburi, Thailand	Penang, Malaysia	Banda Aceh, Indonesia	Manila, Philippines
Annual GHI [kWh/m^2] (source)	1838 (SERL/DEDE satellite*)	1794 (Meteonorm v7)	1701 (Meteonorm v7)	1779 (Meteonorm v7)
Annual average ambient temperature [°C] (source)	28.36 (TMD**)	27.88 (Meteonorm v7)	27.65 (Meteonorm v7)	27.85 (Meteonorm v7)
PV module tilt angle [degrees]	15	5	5	14
Uplift	2.7%	0.3%	0.3%	1.4%
Global inclined irradiation [kWh/m^2]	1888	1799	1706	1804

* Solar Energy Research Laboratory satellite-based data, Silapakorn University, together with Department of Alternative Energy Development and Efficiency, Ministry of Energy, Thailand

** Thailand Meteorological Department

Table 4. Locations chosen for the comparison exercise.

For this comparison exercise, a fixed module tilt angle is proposed for each location to maximize the irradiation received by the fixed solar modules in each location. The fixed module tilt angles and annual irradiances in the inclined plane obtained from PVsyst are also shown in Table 4.

Simplifying PV performance modelling assumptions

In order to conduct a representative comparison of performance between the two technologies, a number of assumptions have been made for the inputs to the PV plant performance modelling for all cases, specifically:

- Similar PV module installation capacity.
- Similar AC:DC ratio of 1:1.22.
- Fixed ground-mounting structure.
- Similar shading losses (entailing a greater land area for the thin-film plant).
- In certain sections of DC cable installation, DC cable length for the thin-film plant is assumed to be twice that of the polycrystalline module PV plant because of the larger area required for thin-film module installation.
- Similar central inverter model, AC cable size and transformer model.
- Spectral losses are estimated on the basis of the sun angle computed in

PVsyst regardless of actual atmosphere and air pollution conditions.

- No soiling losses, plant outages or grid outages.
- Land is not limited.
- Durability of the plant to perform for a project lifetime of 25 years.

Based on the above assumptions, a typical conceptual plant design for each of the polycrystalline and thin-film plants was developed in order to estimate actual average expected performance in each location. For example, the string configuration was designed to be compatible with a selected central inverter for each PV module technology. The number of modules per string for polycrystalline plants is therefore not the same as for thin-film plants because of the different electrical characteristics of these two PV module technologies.

The power tolerance and mismatch losses in this exercise are based on the actual flash test results of the PV modules used at the two plants considered in the validation analysis together with their respective string configuration designs.

Degradation estimates of 1.00% and 1.55% in the first year of operation, which are derived from the PV module laboratory test results and in-field operational data, were applied for the polycrystalline and thin-film plants respectively. For subsequent years, a degradation rate of 0.50% was assumed and applied for both PV module technologies. The system degradation (inverter, transformer, cable, switchgear, etc.) was, however, assumed to be negligible over 25 years.

The validated PV plant performance modelling (combination of PVsyst and Mott MacDonald in-house modelling) has taken into account the above-mentioned concept design and assumptions together with two selected specific PV modules' specification and laboratory test data. The results of this comparison exercise are explained further in the next section.

Comparison results

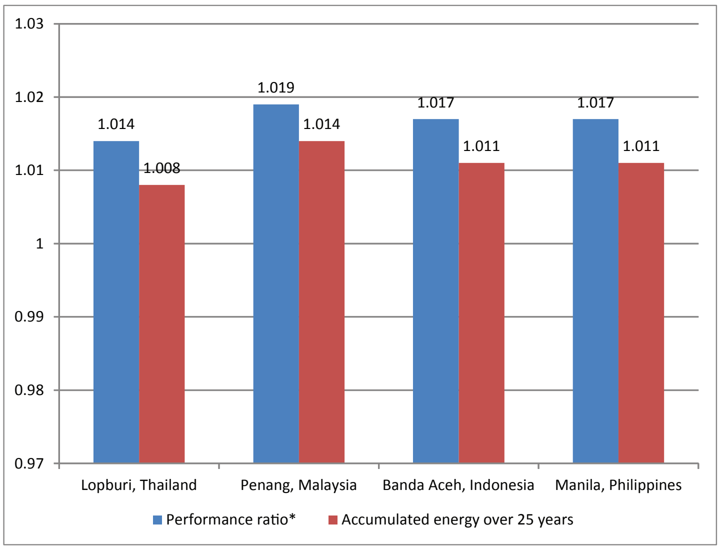
PV performance modelling was carried out for each location (eight PV plants in total). Since the purpose of this analysis is to compare the PV plant performance of two PV module technologies, the normalized modelling results with key PV module losses of the thin-film plants (relative to the polycrystalline plant at each location) are given in Fig. 3.

Fig. 3 shows that over 25 years the thin-film plant can produce around 0.8–1.4% higher energy output than the polycrystalline plant in the selected four locations. This is mainly because of two key module performance factors: temperature losses and low irradiance losses. On the basis of the modelling results, the thin-film PV module's temperature and low irradiance losses are respectively around 50% and 40% lower than those of the polycrystalline PV module, for the two specific PV module models considered here. In general, for the two specific modules in this analysis, the thin-film plant will yield slightly higher performance and energy output than the polycrystalline plant over 25 years.

> "The thin-film PV module's temperature and low irradiance losses are respectively around 50% and 40% lower than those of the polycrystalline PV module."

In order to make a meaningful economic comparison, the levelized cost of energy (LCOE) was also calculated. The LCOE is a calculation of the cost of generating electricity at the point of connection to a load or electricity grid. It includes the initial capital and discount rate, as well as the costs of continuous operation and maintenance. Financial parameters based on the authors' experience of utility-scale solar PV plants in Thailand and the Southeast Asia region were assumed for the purpose of the LCOE calculation, as shown in Table 5.

An equivalent-capacity plant using thin-film PV modules normally requires a larger installed area than one using polycrystalline PV modules: the material and labour cost of thin-film plants for PV module installation, mounting structure, foundation, cabling and land preparation work is therefore higher. On the basis of the breakdown price of EPC work for a large sample of solar PV plants in Thailand, an 18% difference in the EPC price (excluding



*Before degradation rate is taken into account

Figure 3. Normalized modelling results for thin-film plants (relative to the polycrystalline plants at each location).

Financial parameters	Polycrystalline plant	Thin-film plant
PV module price [US$/Wp]	0.60	0.42
EPC price excluding PV modules [US$/Wp]	1.00	1.18
Total EPC price [US$/Wp]	1.60	1.60
CAPEX* [US$/Wp]	2.00	2.00
OPEX [US$/Wp]	54.0	55.5
OPEX escalation rate	4%	4%
Discount rate	10%	10%

*Total EPC price is assumed to be 80% of CAPEX

Table 5. Financial parameter assumptions.

	Lopburi, Thailand	Penang, Malaysia	Banda Aceh, Indonesia	Manila, Philippines
Normalized LCOE	1.001	0.996	0.998	0.998

Table 6. Normalized LCOE for thin-film plants (relative to polycrystalline plants at each location).

PV modules) as a result of this additional work was estimated.

As shown in Table 5, the per unit CAPEX of the thin-film plant is assumed to be equal to that of the polycrystalline plant, because the lower module price is offset by the higher EPC price excluding PV modules. This results from the differences in PV module price and construction work for these two PV module technologies, on the basis of price benchmarks in Thailand and the Southeast Asia region; however, the analysis results will be highly sensitive to actual tender prices, as well as to land prices, which can be expected to vary over time and on a project-by-project basis. Given that land purchase or rental costs vary significantly within and between countries, it is not possible to take into account the relative impact of this in a meaningful way in this comparative analysis. For the study discussed in this paper, a simplifying assumption was therefore made that the solar project company owns adequate land for installing either of the PV module technologies without a land cost impact.

Based on the above assumptions, together with annual energy output results from PV performance modelling as given in Fig. 3, the normalized LCOE results for the thin-film plants (relative to the polycrystalline plant at each location) are given for a 25-year project lifetime in Table 6. The results in Table 6 show that the LCOE in US$/kWh of the thin-film plant differs by less than 1% from that of the polycrystalline plant, with a marginally higher cost for electricity generated by the thin-film plant at Lopburi, Thailand, but lower for other locations. The marginal difference in LCOE shown by this analysis is due to the assumed equivalent CAPEX of both plants, and to the higher OPEX of a thin-film plant (with a greater area to maintain) being offset by higher energy production over the project lifetime.

As mentioned earlier, this comparison exercise focused on two specific PV modules for which the performance had been validated and confirmed to be in line with actual in-field performance through the modelling employed. While the conclusions apply for one specific tandem-junction PV module, a number of other thin-film module technologies (a-Si-based single- or multiple-junction and cadmium telluride PV modules) have a similar performance profile and would lead to similar conclusions. The outcome of an approximately equivalent LCOE is nonetheless sensitive to the specification of the PV modules, along with the other given technical and financial assumptions.

Conclusion

For the two specific models of PV module considered, the results of the study discussed in this paper showed an approximately 1% higher plant yield for thin-film modules than for crystalline modules, under the prevailing climatic conditions of high temperature and diffuse irradiance. Based on the cost assumptions used, the lifetime levelized cost of electricity generation from a PV plant using thin-film was comparable to that of a plant using crystalline PV modules, for all four of the Southeast Asian locations considered.

> "This analysis suggests that thin-film PV module technology would generally be competitive in the Southeast Asia region in terms of technical and economic performance."

While polycrystalline PV modules maintain a dominant position in the current emerging solar market, this analysis suggests that thin-film PV module technology would generally be competitive in the Southeast Asia region in terms of technical and economic performance. To select the best-performing PV module technology for a particular site, however, Mott MacDonald continues to recommend a dedicated study employing, where feasible, a combination of available climatic conditions, PV module laboratory test results, and in-field data from previously operating plants.

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