PlantPredict: Utility-scale PV modelling software for solar project life-cycle assessment

Modelling | First Solar has developed an energy assessment software platform that models the electrical generation of utility-scale PV power plants. This software, called *PlantPredict*, is an enterprise application that streamlines and fulfils many energy simulation needs throughout the project development life cycle, from the site prospecting, through design and optimisation, and contractual commitments, to power plant monitoring. Bodo Littmann and Alex Panchula of First Solar discuss some unique models required for characterising CdTe power plant performance, and outline the PlantPredict tool's use throughout the project development phases, with the goal of ultimately lowering the total cost of ownership of PV power plants

The solar industry is equipped with a variety of PV modelling software packages – such as PVsyst, NREL's Solar Advisor Model, and Helioscope by Folsom Labs – for simulating the energy generation of PV power plants. All of these products allow a PV power plant developer or owner to estimate, with varying degrees of fidelity, the energy generation. First Solar has developed a tool called *PlantPredict* that is integrated with First Solar's information technology and business systems in order to address all four stages of a PV power plant's life cycle. In this paper the core attributes of the PlantPredict tool are discussed, along with how its business integration is used to refine the energy estimate over the life cycle of a PV project. The validation of its accuracy in estimating power plant energy generation is also presented. An in-depth analysis of PlantPredict's accuracy when compared with operating power plants has been performed by Passow et al. [1].

Power plant life cycle

The life cycle of the PV power plant includes four distinct stages: 1) site prospecting, 2) design and optimisation, 3) definition of contractual commitment and 4) operation. Each of the stages has distinct energy assessment requirements. During the site prospecting stage, achieving a go/no-go decision on a particular technology or site is the primary focus; this is enabled by fast, repeatable and simple comparisons. During the design and optimisation stage, the chosen site and technology are economically optimised for the actual costs and engineering constraints. Here, the requirement for modelling is a physical representation of an actual layout and the ability to vary parameters so that the lifetime energy output can be fed into economic models. During the contractual commitments stage, the losses assumed in the power plant must be documented and agreed to by means of a complete engineering review, requiring a bankable energy assessment. During the actual operation of the PV power plant, the ability to repeatedly represent the current state of the power plant and easily input actual weather data into the model enables the reporting of actual generation and its comparison with expected generation.

Tool description and architecture

PlantPredict is a cloud-based web application that allows the user to set up and execute individual energy simulations from a library of components. The inputs and outputs of the simulation are shown in Fig. 2.

The weather is a time series of meteorological data, which may be a typical meteorological year of 8760 hourly records of irradiance, air temperature, etc. (e.g. from the NREL TMY3 database [2]). One distinguishing feature of PlantPredict is that the weather input is *not* limited to hourly data; sub-hourly weather measurements from on-site meteorological stations can also be used for power plant

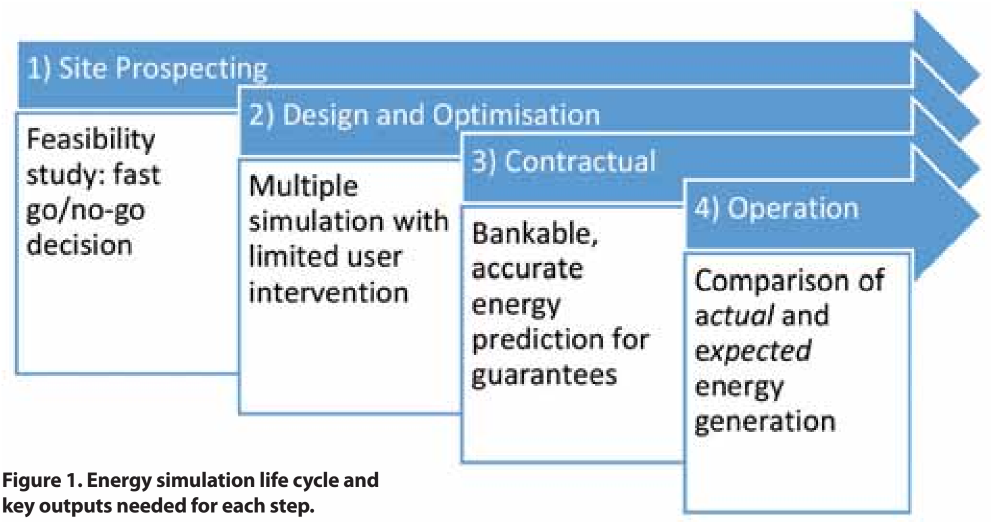

Figure 1. Energy simulation life cycle and key outputs needed for each step.

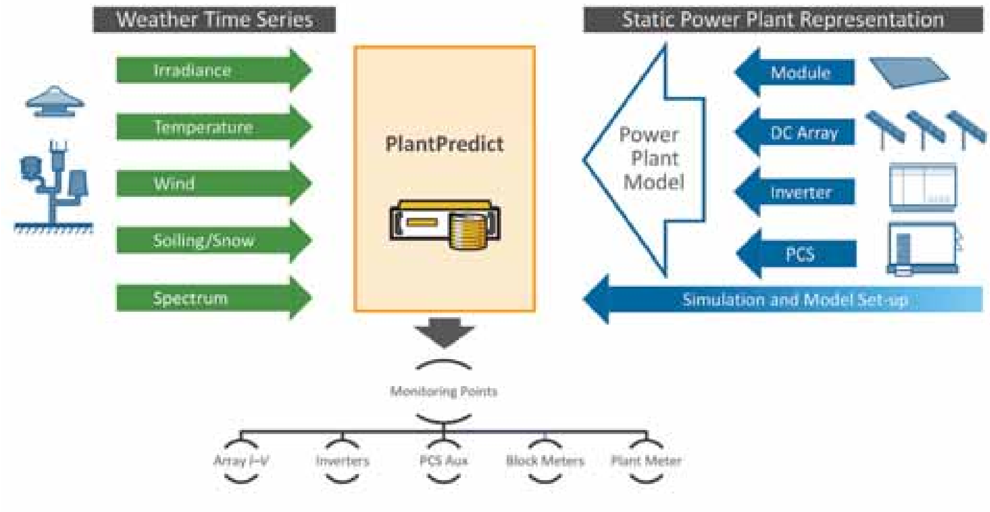

Figure 2. PlantPredict energy simulation overview.

performance monitoring. The power plant is represented by a nested hierarchy of subassemblies, representing a collection of PV modules → DC arrays → inverters → power conversion stations → transformers → transmission lines.

Following standard design practice, the power plant is divided into any number of 'AC power blocks', each of which can have distinct parameters, such as module type, orientation, DC capacity and inverter model. The energy flow is aggregated in the simulation, with energy dissipation factors accounted for and reported in the tool's output. Attributes that are not physical properties of a power plant design layout – such as degradation

"The model of the power plant can be stored as a reusable component in the software and mated with any geographic location or weather record set"

profiles, module mismatch and spectral response – can also be customised at a block-by-block level.

One unique feature that integrates the energy prediction platform with business practices is that the model of the power plant (as well as its subcomponents) can be stored as a reusable component in the software and mated with any geographic location or weather record set. This allows power plant developers to quickly compare the energy of a suite of customised power plants having a wide variety of inputs, directly addressing the 'site prospecting' stage of project development. This flexibility in the overall hierarchy of a PlantPredict simulation is illustrated in Fig. 3.

Business systems integration

PlantPredict can function as a standalone energy simulation software package with a dedicated web user interface; however, its true power is harnessed when coupled with other business systems (see Figure 5). To this end, PlantPredict services can be called via a collection of web APIs (application programming interfaces), either by internal First Solar tools on the server side or by external, customer-facing client web applications. The creation of separate applications via a web API makes the exposure of customised portions of the core simulation toolset possible.

For example, business development partners can log in to a simplified interface that satisfies the site-prospecting needs. At this project evaluation phase, PlantPredict is available in the guise of an 'indicative energy model', an external web portal which restricts the user inputs to basic parameters, such as type of PV technology, mounting technology, AC and DC capacity, ground coverage ratio, and a few select components (e.g. inverter types). Geographic location and weather source selection are map based. There is not a steep learning curve for creating the 'apples-to-apples' comparison: significant training on complex energy assessment software is not required. Despite this simplified interface, the results are generated from a fully fledged hourly energy simulation with many secondary input parameters preconfigured.

Additional functionality can be enabled that allows an automated parametric analysis for design and optimisation. PlantPredict has a library of 'reference power plants' that function as base cases for *parametric* analyses, which allow the variation of DC:AC loading ratios, row spacing, tilt angles, etc. The parametric analysis, through the web API, can be performed by economic optimisation goal-seeking engines that contain project cost data and site boundary conditions. An example of such an optimisation is illustrated in Fig. 4, where an energy simulation is run for a fixed-tilt system, with varying combinations of DC:AC and spacing between collector rows, and all other factors kept constant.

The interplay between tightened row spacing (increased shading loss) and larger DC:AC loading (more total generation at the expense of increased inverter clipping losses) is readily apparent. An optimisation tool that contains a database of project costs and other project information might choose to sweep only the combination of DC:AC and row spacing

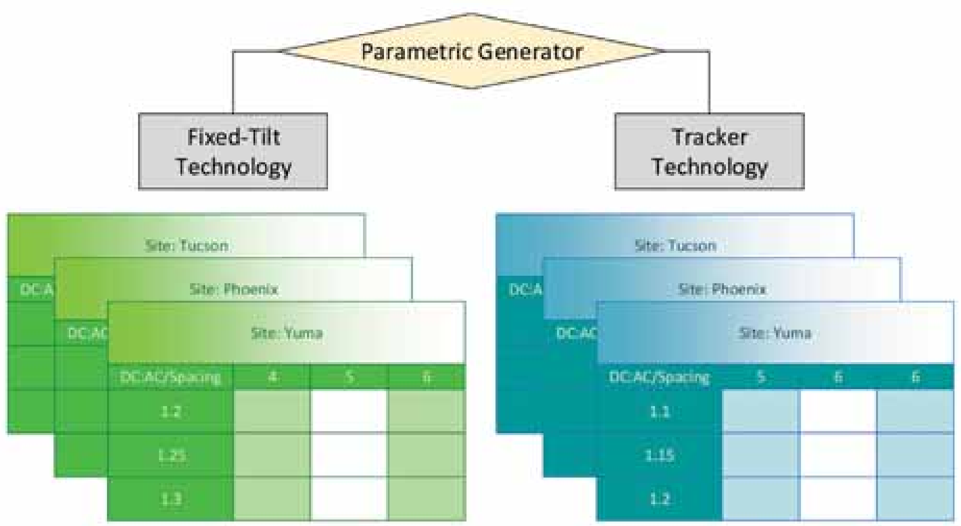

Figure 3. Components of a PlantPredict energy simulation for use in site prospecting with parametric variation.

Quality Assurance and Risk Management of Photovoltaic Projects

Who should be interested in risk management and why?
Good risk management can reduce project failures at a very early stage. Whether on-site, regarding safety, technically, logistically or legally: All of them can result in financial risks. When building large-scale photovoltaic power plants it is essential for stakeholders to look far more closely at how to **minimize risks, assure quality and profitability.**

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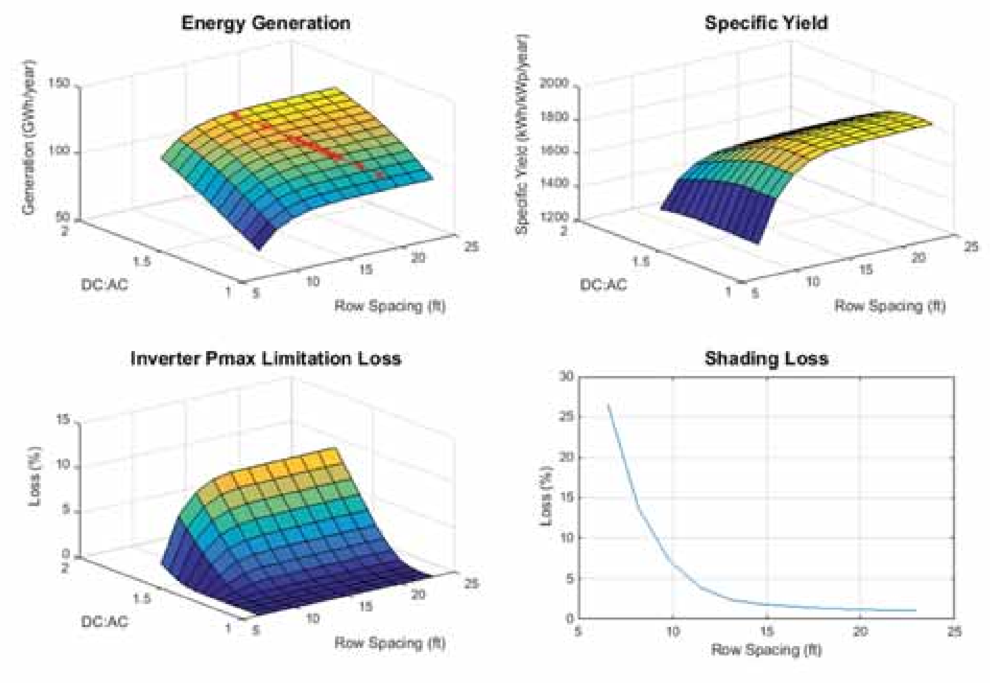
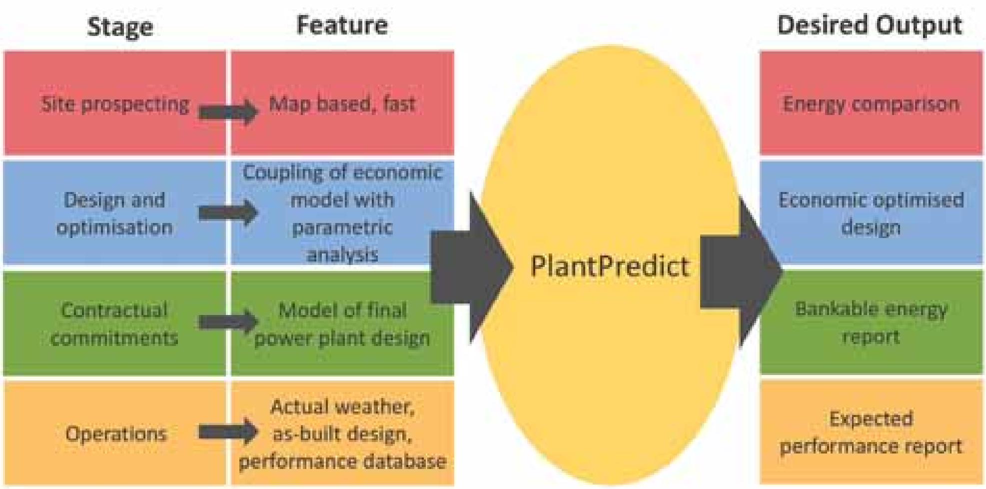
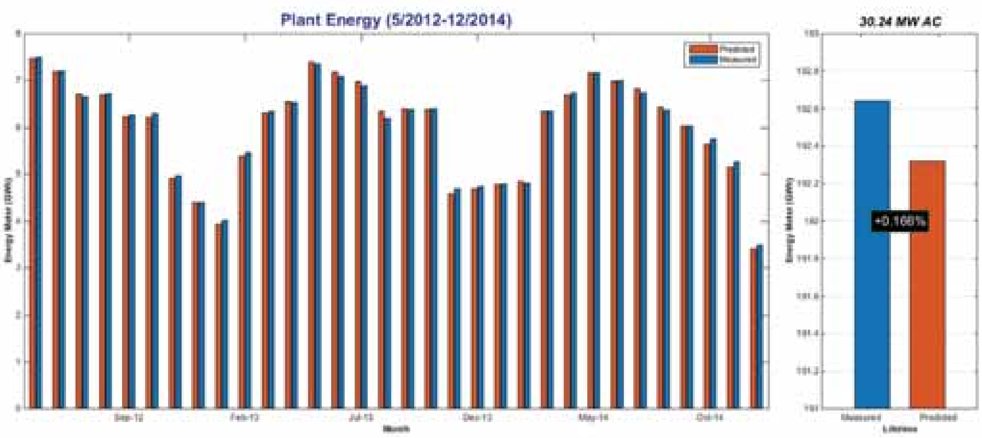


▲**Figure 4. Example of a parametric energy optimisation study for an area-constrained site.**



▲**Figure 5. Tool integration with other business functions.**



▲**Figure 6. Example of weather and outage-adjusted monthly energy report, showing differences between the contractual model (blue) and the actual performance (orange).**

that satisfies an area-constrained site, as indicated by the red line on the top left image of Fig. 4, or the contour of constant land area.

Because of the integration of the toolsets used in the optimisation, the total engineering effort has been substantially reduced, as compared with third-party tools.

At a later stage in the project development life cycle (Fig. 5), as the project design parameters are refined, the layout produced and the solar resource assessed through ground-adapted weather data, the project simulation can be re-executed, continuously preserving a history of all previous simulations in the database. Once the contracted energy model is defined, it is important that it can be reproduced at any time to monitor the performance commitments of the power plant, even as the capabilities of the core PlantPredict algorithms are enhanced in later future software releases.

For operations and maintenance (O&M), PlantPredict has been coupled with the power plant performance database. Meteorological data collected by the on-site sensors are spatially and temporally aggregated, and then batch processed for consumption by PlantPredict. This provides an automated means of reporting the actual daily energy generation, comparing with the contract model and correcting for availability outages and actual weather conditions (Fig. 6). First Solar's O&M team then have at their disposal a comparison point of actual with expected generation for eliminating potential false alarms and improving the allocation of O&M resources.

Algorithms

First Solar has invested heavily in understanding CdTe product performance in the field through a series of models describing its spectral response, module temperature, degradation, etc. The culmination of this work is the implementation of models in a toolset that can be used to assess the value of First Solar power plants in all aspects of the business as well as in its customer base.

The core PV module is represented by a single-diode equivalent-circuit model, with a recombination term in order to better match the *I–V* curve characteristics of CdTe semiconductors. The model used is nearly identical to that implemented in PVsyst [2], but with additional numerical precision extracted for sensitive coeffi-

◀ **Table 1. Key tool features.**

Feature	Description
Solar position	• Implementation of the NREL Solar Position Algorithm [7]
Irradiance	• Erbs, Reindl and Dirint-Disc diffuse/direct irradiance decomposition models [8] • Hay and Perez diffuse irradiance transposition models [8] • Custom incidence angle profiles for reflection and refraction losses, evaluated using a cubic-spline interpolation
Spectral correction	• Precipitable water-based spectral enhancement of FS-3, FS-4 and FS-4-2 CdTe product • Air-mass-based correction for Si technologies
Soiling	• Uniform losses by calendar month • Ramped soiling accumulation model with rain-triggered and manually-triggered cleanings
Degradation	• Multi-year performance estimates
Module temperature	• Simple static model for hourly simulation intervals • Transient model, taking into account heat capacity and all heat fluxes at sub-hourly intervals
Module	• Single-diode equivalent-circuit model with a recombination current term • Non-linear temperature coefficient with a polynomial correction to the diode ideality factor
Inverter	• User-selectable maximum power set-point, derated as a function of temperature and elevation • Efficiency curves at multiple DC voltages
Plant architecture	• Block-by-block breakdown, with independent module models, inverter models, and DC and AC capacities • Staggered block installation and energisation schedule to model sequential power plant block commissioning and independent treatment of degradation
Timescale	• Sub-hourly modelling to avoid modelling artefacts due to weather averaging (inverter clipping)
Weather map	• NREL TMY3 [9] and similar • Web-service access to Meteonorm [10] and SolarAnywhere® [11] • Custom formats for manual upload

cients during the curve-matching process; in consequence, the module characterisations are interchangeable. Ramped soiling profiles [3], the First Solar-specific spectral response of CdTe [4] and a dynamic module temperature model [5] are also available in PlantPredict; these drive improved accuracy of the energy estimation. A diffuse-shading model that simultaneously accounts for incidence angle and occluded sky-view is also included, similarly to the calculation reported by Westbrook et al. [6]. Collectively, these algorithms represent the best known mathematical description of a PV power plant. A description of algorithm features is shown in Table 1.

To overcome some of the limitations of commonly used algorithms in other energy assessment platforms, PlantPredict uses an advanced suite of recently developed algorithms that more accurately represent the physics involved in PV energy generation. One technology understanding that can drive significant value in a project's total return is highlighted below, namely *spectral correction*.

The nameplate power of modules is specified at standard test conditions (STC), which include the ASTM/G173 spectrum, commonly called AM 1.5 [REF]. However, the spectrum of incident light on the module in real-world conditions does not follow this reference spectrum [12], particularly in locations distant from the equator and in high relative humidity environments. Most publicly available tools completely fail to address the fact that the wavelengths of light absorbed by a PV module are a subset of the total incident light, and that this ratio changes with atmospheric conditions. To address this shortcoming for the CdTe module, First Solar developed a correction factor that modifies the broadband measured light to the reference spectrum based on precipitable water in the atmosphere [5]. This methodology has been widely circulated in the industry to developers and independent technical advisors, and has been incorporated in bankable energy assessment for the last two years. For First Solar's Tetrasun monocrystalline Si modules (and other silicon-based technologies), PlantPredict uses the well-known air-mass-based correction factor for Si technologies [13]. These corrections can have a significant impact on performance of up to 2–5%.

Tool validation

The validation of a simulation tool is a complex undertaking and needs to accomplish two goals: 1) ensure the compatibility of the simulation results

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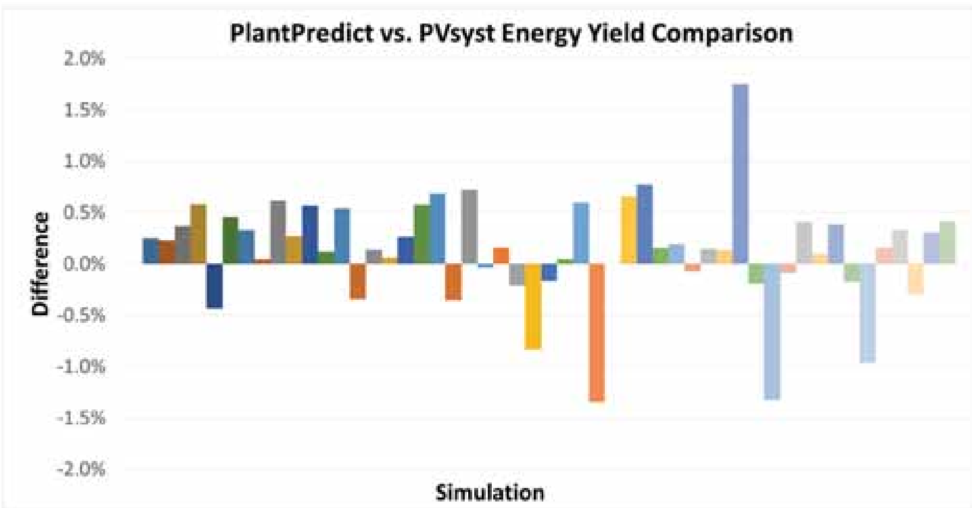
▼ **Figure 7. Comparison of energy generation between PlantPredict and PVsyst for 51 simulations.**



Validation type	No. of sim.	Mean	Standard deviation
Independent assessment	20	+0.20%	1.5%
Comparison with PVsyst	51	+0.13%	0.52%
Expected vs. actual power plant performance	20	-0.41%	2.0%

▲**Table 2. Validation results.**

with those of equivalent tools in the industry; and 2) ensure that the tool's estimates represent the true performance of a real-world power plant. The first can be achieved by unit testing individual algorithmic components (e.g. solar geometry, tracker positioning and module *I–V* curve solving) and comparing the results with those of other tools, insofar as the same fundamental mathematical models are used. The

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validation against actual power plant performance requires a well-behaved, data-complete and well-characterised power plant, as well as a tight coupling of measured meteorological data with power plant performance data (e.g. module temperature, array current and voltage and inverter efficiency).

In order to demonstrate the bankability of PlantPredict, First Solar has performed a three-pronged validation of the accuracy of the tool against actual power plant performance and industry-standard simulation tools. An independent technical assessment was performed by DNV GL [14], which evaluated PlantPredict at four geographic locations under various geometrical orientations (fixed-tilt, horizontal tracker, various azimuths). PVsyst [2] was used as the tool of reference. A more in-depth in-house assessment was performed which compared energy conversion loss factors between PVsyst and PlantPredict for 51 simulations, comprising a mix of recent CdTe product lines including Series-3, Series-4 and Series-4-2 modules, and different inverter models, array orientations, geographic locations and climates, as shown in Fig. 7.

PlantPredict's energy estimates were also compared with the cumulative performance of 20 operating First Solar power plants commissioned between 2009 and 2013, comprising more than 950MW_{DC} of installed product across a wide range of climates [1]. This is an expansion of work on a single hot-climate site presented previously [15]. DNV GL also independently validated the techniques used in filtering and preparing the power plant data prior to applying it as an input to the simulation tool (see Table 2).

One final aspect, from a bankability perspective, is the ability to regenerate performance models based on past versions of the tool, or on other, older configurations of model settings. A tight revision control system, along with an accompanying regression test suite, is required, as contractual performance models need to be maintained and executed for many years, even as the core tool functionality evolves.

Conclusions

As the deployments of PV power plants become more frequent, reducing the life-cycle cost of these projects is increasingly important to their total economic value. First Solar, as a major provider of utility-scale PV power plants, has developed a leading-edge prediction toolset that underpins the expected performance of these assets in real-world conditions. PlantPredict, through its integration with business practices and a web API interface, provides unique flexibility in addressing all stages of the project life cycle. The advanced algorithm suite also offers a superior level of energy assessment accuracy that is not found anywhere else in the marketplace. PlantPredict is available to select First Solar partners in 2015.

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