PV System Reliability: An Operator's Perspective

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***Abstract*—The long-term performance of a photovoltaic (PV) system is one of the fundamental sources of its value; the other being the unit value of the energy it is generating. The industry operates under the assumption that a PV system can keep converting photons to electrons quite reliably with minimal interruptions in service for the typical 20–25-year duration of the energy purchase contracts. However, manually assembled macroscopic systems, comprising components with a high quotient of manual labor, and which operate outdoors under noncontrolled conditions, do tend to exhibit issues. The inverter software which is critical for their operation is an additional potential source of failure. In the case of an operator with global presence, relying on local assembly crews and sourcing components from a large number of suppliers, the challenge in keeping hundreds of power plants in optimal operation with regional teams of roving technicians cannot be easily overstated. Outages of mission-critical subsystems comprise 69% of identified service issues and are responsible for 75% of the associated energy losses. Most of the issues manifest at the inverter, but ac subsystem failures and externally caused outages comprise a large share of the biggest losses. Module failures represent a small fraction of identified issues.**

***Index Terms*—Inverters, modules, photovoltaic (PV) systems, reliability.**

I. Introduction

RELIABILITY is a concept that can be used in both casual and technically exact contexts. Toward the latter end of the spectrum, system reliability is defined as "the probability that a system, including all hardware, firmware, and software, will satisfactorily perform the task for which it was designed or intended, for a specified time and in a specified environment" [1]. In practice, a photovoltaic (PV) system is a compilation of systems and components, ranging from simple hardware like wire interconnects to complex units like tracker controllers and inverters, which makes the rigorous treatment of the overall system reliability a challenging task, but one that is essential to the on-going maturation of the industry. It is critical for the operator to be able to assess system reliability in order to optimize decisions in design, engineering, procurement, construction, and service.

The first step in assessing the reliability of the whole system is to define satisfactory performance according to design, which is a challenge in itself. Availability is one such basic metric, but is more applicable to subsystems, such as the inverter or the ac subsystem. The primary shortcoming of a simple application of availability as a metric for PV systems is the fact that all hours are given equal weight. This is inconsistent with the primary economic driver of PV, which is currently energy generation. A metric that provides better alignment is the ratio of the measured generated energy to the value estimated by a model. Such a ratio or index can inform the operator about performance relative to the expectations that were set during the design of the plant or to a theoretical level of production based on historical data.

When analyzing PV system performance, it is important to recognize two distinct classes of failure: outage and impairment. An outage is a situation where the entire system or critical subsystem is unavailable for production. By contrast, an impairment is a situation where the system continues to operate but at a level below expectations. This is an important distinction for several reasons. Impairments take longer to manifest and more sophisticated analytics to identify, and in many cases do not justify immediate corrective action. Outages, on the other hand, are nearly impossible to miss, relatively easy to characterize, and require immediate attention.

The systems considered in this study are actively monitored at the meter and the inverter level. Despite the fact that impairments are inevitably underaccounted, SunEdison experience indicates that outages dominate in terms of production impact. The following study considers both outages and impairments; however, any consideration of whether increased granularity of monitoring is justified by cost-benefit analysis is outside the scope of this paper.

Still, a plant that exhibits frequent equipment failures will prove expensive to operate in order for it to meet its long-term performance levels: a reliable PV system can meet its performance goals with the most economical operation. The cost of unreliability manifests in two ways: the value of unrealized production and the cost of repair. When components fail during their warranty period, the repair costs (driven by the dispatch of service staff) scale with the failure rate. Therefore, the production impact is a proxy for the sensitivity of the system to a component's reliability, while the failure rate of a component can be used as direct proxy for its reliability.

A. Ticketing Philosophy

A standard procedure in service environments is to log issues in a database. These records contain information relevant to the issue such as time of discovery, system and device impacted, notes from the field personnel, production impact, cost of service, etc.

In this paper, we analyze tickets issued by SunEdison's Renewables Operation Center (ROC) in Belmont, CA, where operators monitor data from the worldwide fleet collected by the SunEdison Environmental and Energy Data System which interfaces with a number of subsystems and components of the

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power plant (e.g., the generation meter, the inverter, the weather station, etc.) and transmits the information to the enterprise database.

In order to allow systematic studies of outages and impairments, SunEdison has defined a two-category, two-level classification system: one category ("Failure Area") contains information about the item which exhibited an issue; a second category ("Root Cause") tracks the reason behind the issue. Within each category the information is captured at two levels: the general and the specific. The general failure area refers to one of the major subsystems of a PV system: PV Module, support structure, dc subsystem, inverter, ac subsystem, weather station, communications, meter, external (for issues manifesting beyond the generation meter). Each general area contains specific areas which correspond to components that comprise each subsystem.

A similar methodology is applied to the root cause category where issues are attributed to construction errors, part failures, and software errors. In order to categorize all instances of lost productivity, causes such as external and preventive maintenance are also included. For each general root cause, one can select a specific one, e.g., mechanical or electrical construction, vendor or SunEdison software, etc.

B. Fleet Description

As of this writing, SunEdison operates more than 600 PV systems in four continents. The systems range in size from a few kWp to 70 MWp with the oldest one constructed in 2005. They contain more than 1500 inverters from 16 vendors and more than 2.2 million PV modules from 35 manufacturers. Almost all high-volume cell technologies are represented in the fleet, with crystalline Silicon having the lion's share (>60% by units), followed by CdTe and amorphous Silicon products.

II. Results

A. General

The results presented in this paper are based on the analysis of more than 3500 tickets which were issued between January 2010 and March 2012 (27 months) for 350 systems designed and operated by SunEdison. The energy production that was not realized due to the issues captured in the tickets was 6.5 GWh, corresponding to less than 1% of the energy produced during the 27 months under investigation.

To the extent that each service ticket corresponds to an abnormal state of the PV system, the Pareto tables (see Tables I and II) of tickets and the associated energy impact, grouped by failure area and root cause, can facilitate a more detailed reliability analysis.

The fact that most issues manifest at the inverter is no surprise based on the complexity and active operation of the inverter relative to the rest of the system. These results are consistent with findings reported since 2009 [2]. Since the incapacitation of an inverter knocks out all the PV modules connected upstream of it, it comes as no surprise that inverter failures are the biggest cause of lost productivity in PV systems as well.

TABLE I
FREQUENCY OF TICKETS AND ASSOCIATED ENERGY LOSS FOR EACH GENERAL FAILURE AREA

General Failure Area	Pct of tickets	Pct of kWh lost
Inverter	43%	36%
AC Subsystem	14%	20%
External	12%	20%
Other	9%	7%
Support Structure	6%	3%
DC Subsystem	6%	4%
Planned Outage	5%	8%
Modules	2%	1%
Weather Station	2%	0%
Meter	1%	0%

TABLE II
FREQUENCY OF TICKETS AND ASSOCIATED ENERGY LOSS FOR EACH GENERAL ROOT CAUSE

General Root Cause	Pct of tickets	Pct of kWh lost
Parts/Materials	52%	48%
External Cause	21%	33%
Software	9%	7%
Other	9%	4%
Unknown	4%	3%
Construction	4%	3%
Preventive Maintenance	1%	1%

However, as the inverter contains most of the intelligence of a PV system, its failures are also easier to capture. Subsystems upstream of the inverter are rarely monitored at a resolution that would allow a direct report of a malfunction. It is important to note that communication failures are on par with inverter-related issues in terms of frequency, but they are not counted along with the rest of the failures because they are transient and do not impact production.

The ac subsystem, comprising everything between the inverter and the generation meter, comes second in terms of frequency of issues despite its relative simplicity. The high frequency may also be biased by the fact that any failure at the ac subsystem constitutes a full outage of the entire upstream system. This characteristic, along with long lead times in repairs and the frequent need for repermitting, drives the disproportionate fraction of lost productivity attributed to these failures.

Similarly disproportionate to the relative fraction of tickets is the corresponding energy loss during an external outage, which points to the risk associated with grid disturbances and utility mandated shutdowns, i.e., factors that are outside the sphere of influence of a PV system operator.

Module failures comprise a very small percentage of reported tickets and corresponding production loss. The small number of reported issues most likely reflects the rarity of failed modules,

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