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A Best Practice for Developing Availability Guarantee Language in Photovoltaic (PV) O&M Agreements

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ABSTRACT

This document outlines the foundation for developing language that can be used in an Equipment Availability Guarantee, typically included in an Operations and Maintenance (O&M) service agreement between a photovoltaic (PV) system or plant owner and an O&M services provider, or operator. Many of the current PV O&M service agreement Availability Guarantees are based on contracts used for traditional power generation, which create challenges for owners and operators due to the variable nature of grid-tied photovoltaic generating technologies. This report documents language used in early PV availability guarantees and presents best practices and equations that can be used to more openly communicate how the reliability of the PV system and plant equipment can be expressed in an availability guarantee. This work will improve the bankability of PV systems by providing greater transparency into the equipment reliability state to all parties involved in an O&M services contract.

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EXECUTIVE SUMMARY

The operational condition of a solar photovoltaic (PV) system or power plant and its equipment is expressed in terms of “availability.” Contractual definitions of availability incentivize a high degree of equipment up-time because how well the equipment is operating has a direct impact on the amount of energy and, ultimately, revenue that can be generated. A review of existing PV operations and maintenance (O&M) contracts and availability guarantees reveals that many methods are used to calculate availability; some methods focus on equipment while others focus on energy.

With technical assistance from industry, Sandia National Laboratories (SNL) has held working group meetings and web conferences over the past year to improve the availability guarantee language and present it as an equipment-based reliability metric. By analyzing existing availability guarantees within O&M contracts, SNL identified both best-practice elements and gaps that must be addressed to improve communication of equipment operational states and failure modes for the benefit of all parties to the contract. Improved tracking and reporting on availability can also lead to several other improvements: more effective offers and administration of warranties and insurance products; better preventative maintenance and sparing plans; and faster response times for reactive maintenance.

For defining availability and examples on how to calculate both the component and system-based availability, a complete understanding of site-specific conditions is necessary as PV systems that do not incorporate storage need to have a well-defined operational window based on when the “fuel” is available to turn the system on. This paper introduces the concept of tracking raw time-based availability, which is the equipment availability without any excluded events, and using it to inform and compare to the contractual availability, which should also be time-based. The contractual availability has a number of exclusions and rules that consider site-specific conditions when an event that leads to equipment down-time is counted against the owner or the O&M provider.

Other areas of discussion include the concept of partial availability based on the degraded state of a certain piece of equipment, and presents the use of an irradiance-weighted availability which could incentivize O&M activities around minimizing the potential for lost energy production.

To express when to apply the different equations and measurement locations for availability guarantees in an O&M contract, a system classification was developed based on the data granularity needed for calculating raw availability at different locations in the system. This classification is intended to help identify what equipment is necessary to make accurate measurements and satisfy contractual language.

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NOMENCLATURE

ac	alternating current
ANSI	American National Standards Institute
BOS	balance of systems
C&I	Commercial & Industrial
CM	corrective maintenance
CMMS	computerized maintenance management system
CSP	concentrating solar power
DAS	data acquisition system
dc	direct current
EPC	engineering procurement construction
GADS	Generating Availability Data System
GHI	global horizontal irradiance
GW	gigawatt
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IV	current-voltage
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
m	meter
MLPE	module level power electronics
MTBF	mean time between failures
MTTR	mean time to repair
MW	megawatt
MWh	megawatt-hour
NERC	North American Electric Reliability Corporation
O&M	operations and maintenance
PM	preventative maintenance
PPA	Power Purchase Agreement
POA	plane of array irradiance
PR	performance ratio
PV	photovoltaic
SCADA	supervisory control and data acquisition
SNL	Sandia National Laboratories
SREC	Solar Renewable Energy Credit
W	Watt

1. INTRODUCTION

Photovoltaic (PV) distributed generation (residential and commercial) and PV utility or commercial/industrial power plants [hereinafter, both referred to as "PV system(s)"] are being installed at increasing rates across the U.S., with over 20 GW installed as of late 2015. PV systems are an ever-increasing share of annual new generating capacity, with 32% of new generation in 2014 coming from PV and concentrating solar power (CSP) (SEIA, 2015). These PV systems are designed for an economic lifetime that varies between 20 and 30 years, primarily based on warranty considerations and power purchase agreement (PPA) contracts. During its lifetime, the PV system may have one or multiple owners. As with any power generating technology, operations and maintenance (O&M) activities are necessary to maintain a high degree of equipment up-time to ensure that performance and revenue generation targets are met.

Despite the lack of moving parts for PV, several factors can impact the system's overall performance: site and environmental impacts, specification and design choices, workmanship, and other internal or external factors. Contracts are necessary both to define and ensure a high level of reliability or, over long periods, "availability," and typically define the O&M services that fall both within and outside of an operator's responsibilities. In the case of PV systems, these contracts include both *performance guarantees* and *availability guarantees* that are mostly separate, though sometimes linked. As PV is unique in terms of its "fuel variability," mixing performance (with a high degree of solar resource uncertainty) and equipment creates a challenge for reporting on the reliability state of the PV system and to what degree it will be available to produce electricity. For example, many events, including faults and failures can be masked when a contract requires reporting only on energy performance, which incentivizes kWh produced and performance ratios over a deeper understanding of equipment reliability. This masking can also occur when portions or sub-portions of a system fail, with preventative and corrective maintenance postponed or not required for systems with high dc overbuilds.

Another challenge has to do with understanding the equipment status in terms of whether a component is operating as specified by the manufacturer. A partially de-rated piece of equipment may still facilitate energy production, but at a reduced capacity. That begs the question of whether the equipment is available to do the work and how that should be measured in an availability analysis and reflected in an availability guarantee. The ability to measure that reduction and inform reliability and financial analysis is currently limited due to existing monitoring technology, including the cost of instrumentation as well as the use of accurate thermal and electrical models that can capture and model the expected and actual equipment state.

In this paper, we outline supporting material that can be used to develop language for a model availability guarantee with an equipment reliability focus. This document will inform the industry about clauses, definitions, and exclusions that will introduce greater transparency and certainty between parties within this part of an O&M services agreement. The steps taken to develop this language include the following:

- Review of existing O&M contracts for availability guarantees, including other sections that are referenced from, or to the guarantee.
- Draw from the Sandia National Laboratories (SNL) PV O&M working group discussions, to
    - summarize common challenges with existing availability guarantees,
    - highlight the "gaps" identified by industry,
    - present existing model language used by industry for availability guarantees,
    - outline definitions that will be used in a model availability guarantee,
    - provide considerations and arguments to develop new best practices, and
    - provide a rationale and context for sections used in a model availability guarantee.

It is the intention of the authors and the O&M working group participants to offer this language as a template that can provide greater transparency, benefitting all parties in the O&M contract. Other definitions and more complex calculations can be added to the foundation presented in this paper.

This paper and model availability guarantee do not directly address how to calculate, or develop language for liquidated damages, where a lack of contractual availability, i.e., unavailability, is tied to lost performance. That is a contractual detail beyond the scope of this research. In addition, this paper does not address PV systems with energy storage. As PV with energy storage installations increase, the availability language will need to be modified due to the ability to fully provide energy and other grid services during non-daylight hours or under partial and full shutdown states; this will require greater exploration with the working group, including independent engineers, system owners, and operators that are designing, deploying and maintaining PV systems with energy storage. PV systems with high dc to ac ratios are not covered in detail in this paper, but are discussed briefly. Additional data and research is necessary to adequately develop best practices for these types of systems.

2. MOTIVATION

As PV installations grow in number in the U.S. and around the world, O&M professionals that can perform quality maintenance activities and troubleshoot issues in a timely manner are in high demand to ensure PV system revenue targets are being met. The O&M contract between the owner and PV system operator drives the level and quality of those maintenance activities, whether well designed or not; the omission of important details may impact the long-term financial viability of that PV system. Currently, no certification or training programs for O&M providers exist, and a lack of both national and international standards makes it difficult to quantify whether existing practices will lead to high levels of up-time and trouble-free operations. The availability guarantee may fall victim to some of the challenges described above as well as other challenges having to do with how the PV system was specified, designed, installed, and commissioned.

A successful availability guarantee should share responsibility, i.e., risk, appropriately, and incentivize a high degree of *equipment* up-time. Performance of the system in terms of kWh produced will reflect the equipment up-time; however, due to the intermittent nature of available solar insolation and stochastic nature of equipment events, the energy produced when compared to expected energy is not 100% correlated to the equipment being able to perform its intended function. Industry experts have stated as much in terms of what contractual availability should be when focusing on equipment reliability:

> *Availability. In the context of O&M, the percentage of time that a system is operating properly is referred to as its availability… System availability is critical to the overall physical and economic performance of the plant. Availability in the solar service industry has suffered from absurdly low projections. An availability of 98% for a 10 MW facility means that every inverter is off line for more than 7 days every year. This is not acceptable. Scheduled and unscheduled maintenance for monitored power electronics should be able to achieve 99.9% availability.*[1]

Contractually, this level may be achievable aside from external or Force Majeure ("act of God") events, and ensuring performance is not embedded in the availability guarantee. The challenge is other non-monitored equipment and power electronics can adversely impact performance, but not impact what will be defined as the "raw availability," and calculation of contractual availability if those components are not tracked and not included in the availability guarantee.

Some O&M contracts have availability guarantees, others have performance guarantees. Some contracts have both, and some contracts embed performance metrics in an equipment availability calculation. The availability guarantee in an O&M contract or service agreement should be entirely separate from any performance guarantee, in that any calculation of availability is solely focused on understanding the reliability state of the equipment. Time-based data provides a foundation for improved maintenance activities that employ reliability engineering analysis and

[1] http://solarprofessional.com/articles/operations-maintenance/large-scale-pv-operations-and-maintenance?v=disable_pagination

results. It is also recognized, however, that performance depends on the equipment reliability and availability. Other efforts to standardize performance and energy testing, monitoring, and reporting are ongoing, and the authors are well aware of equipment impacts to performance. This paper is primarily focused on the methods for data collection and analysis both to characterize and report on the *equipment* health to the greatest accuracy possible with current configurations and monitoring/sensing capabilities.

Presented in Section 5.7 are equations and definitions for availability, where a time-based "raw availability" is proposed along with a discussion of exclusions that lead into an availability calculation that is compared to a contractual availability value. The appendix provides examples of how to calculate a raw component and system-level availability with examples of availability being measured at locations besides the inverter. An availability classification system is also presented to help distinguish different levels of granularity based on the PV system's monitoring needs.

3. AVAILABILITY AS A RELIABILITY METRIC

Availability is a term widely used in many industries to describe a component's operational state, which is a reflection of its reliability. At its core, it is a measure of whether a component in a system is capable of performing or completing the operation that it was designed for. Typically measured using a binary integer, the equipment is either available (1) or unavailable (0) to perform that task over a specific period of time. Where the definition becomes more nuanced is the timeframe to be measured, determining the source of a disturbance that is preventing that item from performing its intended operation, and how to categorize the availability state of equipment operating out of specification. For example:

- The equipment is ready to operate, but is in standby due to an operational decision.
- The equipment is operating, but in a partially degraded state due to a known wear-out mechanism.
- The equipment is operating at a reduced set point due to external direction or decision.

What is the availability state of the equipment in each case? What is its relationship to system performance? How availability is defined should be unique to the equipment that is being tracked, and delivered in a language that stakeholders can understand and apply successfully.

To put the availability guarantee *contract language* into perspective, an understanding of where the language originated from is warranted. What the industry is currently dealing with for fleet-wide O&M of distributed generation and utility-scale O&M is a relic of availability guarantees primarily intended for traditional fossil fuel, nuclear and hydroelectric power plants that are not respectful of the different taxonomies and metrics that are essential for addressing PV system performance, revenue and condition status.

Transferring this type of guarantee without considering the unique environmental and operational impacts, and fuel source characteristics of PV can result in widely differing contract language that

- is difficult to agree upon based on assignment of risk,
- is difficult to interpret when making warranty or insurance claims,
- may place performance guarantees at cross-purposes with maintaining a high degree of reliability, and
- focuses on the inverter as the primary measure of system availability, potentially missing other equipment issues.

The terminology for reporting on the availability of electrical generating equipment was developed into an IEEE standard in 1987 and updated in 2006 (IEEE Std. 762-2006).[2] This standard was developed well before large-scale renewable energy sources such as wind and PV were integrated into the transmission and distribution grids. As stated in the Overview:

- "*Reliability in this standard encompasses measures of the ability of generating units to perform their intended function*"
- The availability is measured as *"…the fraction of time in which a unit is capable of providing service and accounts for outage frequency and duration."*

This standard states that availably is a function of reliability. Because reliability is important to grid operators, traditional large power plants collect data to report on availability states to regulatory bodies such as the North American Electric Reliability Corporation (NERC).[3] Recent efforts have been made to develop availability language for wind, following IEEE Std. 762 (NERC, 2015), and a report by Hill et al. (2015) outlines a potential availability data information standard for PV for improved data transparency and sharing, and if regulatory compliance becomes necessary. These efforts play a supporting role in improving contract language in the availability guarantee by setting up the language, definitions and equations that will eventually be adopted in future contracts as a function of specific reporting requirements.

When considering how to define availability in the context of a PV system, Fife et al. (2010) described the issue when trying to apply IEEE Std. 762 language to inverters as the primary indicator of reliability on the dc side. In their discussion of "time interval" an alternate definition of availability was discussed as a departure from the standard based on the fact the PV system does not have the fuel to operate continuously; daylight hours above a certain irradiance threshold vary and impact the ability of the PV system to produce energy, though the equipment may be 100% available during a 24 hour period. Their approach reveals the importance of a well-defined availability metric, whether for reliability analysis or meeting contractual terms.

The challenge for industry today is that the consequences are generally well known from faults and failures, but the *occurrence* of certain failures and the degradation pathways that lead to that failure are not well known. The failures and pathways are difficult to predict due to the lack of long-term reliability data. Even *less* well known is the detectability of specific events, which is a function of where and how to measure these events.

Though not addressed here, as battery-connected PV systems increase over time due to markets created for the variety of additional services that storage can provide, the contractual availability

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[2] IEEE Standard Definitions for Use in Reporting Electric Generating Unit Reliability, Availability, and Productivity

[3] NERC requires large generators to meet specific reliability requirements, reported to the Generating Availability Data System database. These requirements, however, do not yet extend to wind and solar, although wind may be first as there are already voluntary reporting databases that have been created to match the updated outlined in NERC (2015). See also http://www.nerc.com/pa/RAPA/gads/Publications/GADS---Mandatory%20Reporting%20of%20Conventional%20Generation%20Performance%20Data%20Final.pdf

language will continue to expand. For example, PV and storage can shift production profiles (whereby a sun up to sun down reference to availability would not suffice), provide back up energy delivery even if an inverter is off-line, and perform additional grid services that have a quantifiable value. The backbone to these services is a highly reliable system evidenced by high equipment availability.

4. PURPOSE AND LANGUAGE OF AN AVAILABILITY GUARANTEE

Availability is a measure of PV system component, sub-system and/or system operational health on both the dc and ac side. That operation is ultimately conveyed in terms of system performance with multiple metrics that can be used to express energy production. For most systems, the dc side makes up a majority of the balance-of-system (BOS) equipment and is the focus of maintenance activities. However, availability guarantees are structured to typically measure the output from the inverter on the ac side to quantify inverter up-time.

A role exists for a performance guarantee and/or availability guarantee in an O&M contract. If both are included, a best practice is to keep the metrics separate until a liquidated damages scenario is in place. The reason for separating availability and performance is that the fuel variability is very high with PV systems and reliability projections are not typically done. Models developed and calibrated over the first few years of a PV system's lifetime may still be highly inaccurate, depending on the PV system architecture and performance model used (Hansen et al., 2013; Stein et al., 2013; Rudie et al., 2014; Hansen et al., 2015) as well as weather and climate fluctuations that exhibit regional impacts not foreseen at project conception (Muller et al., 2015). For example, a report by Vaisala (2014) points out large global horizontal irradiance departures from normal in 2014 for the east and west coast areas of the U.S., indicating that performance models need to be continually evaluated as error estimates will change over time. Another reason to separate performance from availability is that standardized energy tests currently under development need to exclude all downtime; availability measures for critical equipment are *highly dependent* on downtime, with exclusions made that can vary between contracts.

Variability is to be expected, but the performance model can go only so far in accurately representing that variability and uncertainty. None of the commercially available PV performance models have the ability to simulate equipment events and failures in a probabilistic manner; therefore, including a performance ratio in an availability calculation may introduce fuel variability and inaccurate estimates of equipment reliability that can oversimplify as well as underestimate how the equipment should operate. Resolving this model error can be done with an adjustment for irradiance underperformance in the performance ratio calculation, though that differs from the purpose of having an availability guarantee focused on maintaining equipment up-time.

Using the *time equipment was unavailable* to determine lost energy production when equipment availability impacts performance can be viewed as a best practice. Looking at system O&M from this perspective, if done correctly, can help improve plant performance and provide greater support for performance measures that owners and lenders rely on for tracking kWh production for revenue generation.

4.1. Review of the Operations & Maintenance Contract

For any PV system being operated by a third-party, an O&M contract is set in place between the owner of the PV system and that operator.[4] Asset managers are sometimes involved and facilitate activities between the PV system owner and all of the subcontractors providing both operational and maintenance activities. As PV systems become larger and more complex, specialized skills are necessary for troubleshooting and conducting certain preventative and corrective maintenance activities. These operators, also known as PV O&M service providers offer a range of skillsets to ensure that lifetime O&M activities can be performed for an agreed-upon amount. The total budget is determined before the PV system is built and is generally not re-negotiated between the owner and O&M service provider, though negotiation does occur on the language used in the guarantees, which will ultimately be reflected in the profitability of the system to each party; the owner strives to stay under the budgeted O&M amount during their period of ownership while the O&M service provider works to make a profit based on how well they execute elements of that contract. According to working group members, the budget available in the O&M contract is generally not high enough to maintain the high levels of availability outlined in the scope of work.

The O&M activities conducted during the first few years of the PV system's lifetime are typically performed by the engineering, procurement, and construction (EPC) contractor, and then handed over to the O&M service provider.[5] Workmanship and other warranties provided by the EPC contractor continue to some degree into the O&M service provider's contract timeframe. When the O&M contract is developed, negotiation over terms and conditions is a function of the risk appetite between the owner and operator, which will be different when the EPC provides early-stage O&M and the O&M service provider offers middle to later stage O&M. How anticipated and unanticipated events play out over the lifetime of the contract are a function of how well each party understands the risk they are accepting, and the degree to which they can assume that risk and still make a profit. For example, the degree to which the EPC contractor performs O&M activities in the first few years of operation, documentation of early wear-out failures, or proximity to inverter manufacturer warehouse and service technicians may result in negotiation over service response times, which impacts how the availability 'clock' starts and stops in the availability guarantee. It may also result in negotiation of "out of scope" maintenance that can be completed by the provider when requested by the owner, but outside of the contracted budget amount.

Assumptions made during O&M contract negotiation must be recognized as such. Perfect information is generally not achievable due to numerous assumptions regarding the initial quality and long-term reliability of the equipment chosen during specification, design of the system, and

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[4] Internally managed O&M by a utility or an owner-operator use in-house guidelines and best practices that resemble elements in an O&M contract.

[5] Vertically integrated providers may keep the O&M activities in-house and not subcontract to a third-party O&M service provider, or subcontract portions of the services. E.g., vegetation control, washing, plant security.

the skill and capabilities of the installation team. The disadvantage to the O&M provider is that they typically do not participate in the design, specification, construction and commissioning stage. This is reflected in how they negotiate terms with regards to how availability and performance targets should be met. It has been expressed to the authors' that lately, developers are requesting input from O&M providers knowing that their field experience can lead to improved design decisions that increase equipment reliability, availability and performance. It is also worth noting that a plant-level certification process is under development, which has the potential to improve on many of the areas of specification, design, commissioning and O&M that can lead to a quality PV system.[6]

4.1.1. General O&M Contract Elements that Impact Availability

Eleven redacted O&M contracts were reviewed, all provided by SNL O&M working group members.[7] Only four of those eleven contracts included language on availability guarantees. It was not entirely clear if that section was omitted or just not included for a few of those contracts. The working group members have stated that the wide variety in contract language is a function of plant ownership type, company experience, the presence or absence of a PPA, and fleet vs. single site O&M, to name a few. None of the full O&M contracts included both availability and performance guarantees, though a few individual clauses provided by working group members (outside of a full O&M contract) did include both and are discussed in more detail in Section 4.2.

Table 1 below presents the general elements of an O&M contract that have connection to the availability guarantee. The purpose of the table is to help reveal the interconnection between different sections and clauses in the main contract with the availability guarantee.

Table 1. Reviewed PV O&M Contract Elements

Sections	Connection to Availability Guarantee
Definitions	Availability and Force Majeure can be defined early in the O&M agreement, or in just the appendix. Each definition and calculation of availability and percentage for the guarantee can vary.
Scope of Services/O&M Services	This generally covers visual inspection, cleaning and maintenance, reporting, timing of activities, etc. Following this schedule is intended to outline responsibilities and sometimes exclusions. Following these services will outline what is and is not included in the availability guarantee, with respect to the time it takes to remedy the equipment issue and whether or not that counts against the contractual availability calculation.
Repair Services outside contract	In areas that are not covered in the main scope of services, such as repair after a Force Majeure event, this outlines how repairs are to be made, and

[6] The IEC is developing the IECRE-PV plant certification standard which aims to better recognize PV as an asset class. This can create additional value for the PV plant as it will make it easier to make direct comparisons across different plants and allow for regional benchmarking. To implement this, rules of procedure and operational documents are currently under development.

[7] Detailed information on site name, location, penalties and other information deemed sensitive by the working group member was removed. Removal of this information did not adversely impact our ability to pull out pertinent information related to the contract.

	who covers costs of those repairs. Events outside the operator's contractual liability do not count against the contractual availability calculation.
Monitoring Equipment	The granularity of the monitoring equipment in terms of 'where' monitoring occurs and 'what' is being monitored aids in the availability calculation. For example, if availability is calculated at a combiner box, the monitoring equipment needs to include sensors to provide data for that calculation.
Availability	When defined in the main O&M contract, this term outlines the time period used to calculate the guarantee and the "guaranteed" availability, which is typically an annual benchmark used for comparison. Language in this section points to appendices for the calculation and liquidated damages that result when the annual guarantee is not met. In some cases, a formal definition is provided for the different availability calculations that are used to calculate the guaranteed availability.
Force Majeure	This typically refers to low probability/high consequence events that are outside the O&M service provider's control, and not assigned to the operator for repair within the O&M service contract. The lost energy in these situations may mean lost revenue if that event was not covered by insurance. The O&M service provider may be asked to provide services outside the main O&M contract after a Force Majeure event occurs. These events do not count against the O&M provider when calculating the contractual availability calculation.
Warranty Management	Some O&M contracts have stated that when an item is no longer under warranty, it falls under repair services outside of the contract. In that case, the repair time for that component will not be counted against the contractual availability. It provides an opportunity for the O&M provider to conduct activities outside the anticipated and agreed-upon O&M agreement scope.
Insurance	Insurance elements that impact the availability guarantee include Business Interruption (all-risk), provided by the owner. This protects the owner's revenue stream for a repair or replacement from an event that may or may not have been the fault of the O&M provider. For example, an inverter goes down due to improper maintenance and won't be replaced for one month. Many other insurance products may cover different aspects of the PV system; however, they were not revealed in O&M contract review.
Dispute Resolution	Some contracts have an option for a third-party to review technical disputes that may apply to the availability guarantee. Not every possible circumstance that impacts equipment availability can be anticipated when both parties enter into the O&M services contract.
Performance Ratio	In some contracts, the performance ratio is used within the availability calculation. In others, it is tracked separately though gets used in an availability guarantee liquidated damages scenario. See Table 2 for examples. When used in an availability calculation, it is adjusted by actual site-wide irradiance and measures how well the equipment "performs" in terms of energy production. However, in some of the contracts reviewed for this report, the equations do not reflect on the state of the equipment, as one would expect given the term "availability," but reflected only on the energy the system produces, resembling a performance ratio.[8] None of the contracts reviewed explicitly referred to the IEC 61724 definition of performance ratio.

[8] The performance ratio has many different definitions outside how it is defined in the IEC 61724 standard. Efforts are underway to improve the performance ratio calculation to better account for weather impacts to module temperature (Dierauf et al., 2013) and in a forthcoming revised

Exclusions	Any event that serves to exclude downtime in an availability guarantee calculation such as grid events, Force Majeure, vandalism, certain preventative and corrective maintenance, etc. that falls outside of the contract between the owner and O&M service provider, and liability of the O&M service provider. Some Force Majeure clauses include all the 'excluded' events and go beyond just defining what could be considered traditional Force Majeure items. E.g., earthquake, hurricane, tornado, acts of war or civil unrest, etc.
Preventative/Predictive Maintenance (PM)	This is typically found in an addendum, appendix or annex to the main O&M services contract. By following the agreed-upon schedule, it intends to reduce the O&M provider's liability to some degree when things do go wrong. The premise is that following a PM schedule that respects manufacturer warranties and industry best practices should result in PV system with greater up-time and high availability than a project with no PM. Some PM schedules count against the O&M service provider based on an annual hourly limit. Working group members have stated that component manufacturers are rejecting warranty claims for failed components where it cannot be proven that preventative maintenance has taken place based on the manufacturers recommended schedule.
Corrective Maintenance (CM)	Performing corrective maintenance can fall outside of the O&M services agreement and is sometimes referred to as "additional work." When CM is performed after warranty expiration, some contracts are explicit about how repairs are handled outside of the warranty. This type of activity does not generally count against the O&M service provider's contractual availability guarantee calculation if performed outside of the contract scope.
Availability Guarantee	The area where availability calculations are described and typically found in an addendum, appendix or annex to the main O&M services contract. This will be described in more detail in Table 2.
Performance Guarantee	In some contracts, the performance guarantee measures the kWh output of the PV system against an expected kWh based on a PV performance model. Underperformance can result in liquidated damages, and in some contracts, over performance can result in performance bonuses. An element of the performance guarantee, namely the modeled energy production, is used to calculate liquidated damages when the availability guarantee targets are not met.
Spare Parts	Some O&M contracts provide detailed instructions on who is responsible for spare parts procurement, replacement and record keeping. Being able to keep the spare parts inventory current and parts replaced under the contractual time period is intended to reduce the amount of downtime associated with any type of outage requiring parts replacement.
Liquidated Damages	This applies when the measured availability (and/or performance) is below a certain threshold stated in the contractual availability (or performance guarantee). Amounts paid are typically tied to the performance of the PV system based on the amount of revenue lost and other considerations, typically capped at the total O&M contract amount.

As shown above, many sections both impact and are impacted by the availability guarantee. As the focus of the O&M contract is on keeping the system operational, many of the sections are written to remove ambiguity on the role of the owner and O&M service provider in terms of how

version of IEC 61724. The role of the performance ratio in an O&M contract and relationship to availability is discussed in more detail in this report.

the equipment is to be monitored and maintained. As many of the contracts that were reviewed did not include all of the addendums, it was difficult to make direct comparisons. In addition, there may be elements in O&M contracts not reviewed by the authors that would provide additional context to the discussion. Some of the most important observations related to availability include the following:

- Not every O&M contract specifies an availability guarantee.
- Not every O&M contract specifies a performance guarantee.
- Exclusions in some availability guarantees make it difficult to determine what is *not* excluded.
- The contracts do not state consistently which PM or CM events stop the availability clock and which are counted against the O&M service provider.
- Elements of system performance (available irradiance and kWh produced) are discussed in multiple contracts, and in some cases are integral to the availability calculation.
- No catch-all clause addresses events not anticipated in the O&M contract.

Discussions among the working group members who are parties to O&M contract agreements have confirmed the broad variation in the contract language, which leads to greater uncertainty when trying to interpret contract elements while performing specific activities. This is especially apparent with the availability guarantee and associated equations.

4.2. Review of the Availability Guarantee Language

The availability guarantee is typically included as a clause or addendum to the O&M services agreement/contract. The purpose of the availability guarantee is to ensure that the operator is maintaining the *equipment* as outlined in the O&M contract, and ensuring that it is ready to produce power when irradiance is sufficient to turn on the inverters. What gets calculated on an annual basis in the availability guarantee is a function of how well the system operator can adhere to agreed-upon activities that can fall within and outside the scope of the contract. Those events that end up being excluded 'stop the clock' for considering when the PV system is contractually available, and those that are not excluded keep the clock running and are counted against the O&M service provider. Based on this accounting of equipment uptime, the raw availability of the PV system can be moderately to substantially lower than the value calculated to compare to the contractual availability.

4.2.1. Structure

The main elements in the availability guarantees reviewed for this report are presented below. In the sections that follow are discussions presenting the differences between each guarantee as well as a discussion of impacts the language may have in calculating the availability guarantee and meeting contractual obligations:

- Availability Guarantee and Definition
- Liquidated Damages

- Availability Calculation
- Availability Window and Sufficient Irradiance
- Exceptions and Exclusions

4.2.2. Type of Availability

Out of eight availability guarantees, each was reviewed for the availability calculation and to what degree it included performance or equipment. Based on that metric, four were found to be equipment focused, two were equipment and energy focused, and two were energy performance focused. Of those three that have performance included in the availability calculation, one was more performance-centric compared to the other two (Table 2). It is not clear the system size for each guarantee, nor the reasoning behind why performance was included in some, with others just including availability calculations. It is possible that those that drafted these agreements figured that one calculation for availability and performance would suffice and that based on general practices in the industry, there was no clearly defined awareness of the benefits and shortcomings of the different approaches.

One of the availability guarantees that uses the performance ratio inside the availability calculation references the "quality of the physical and electrical components selected, climatic conditions, and the quality of the installation." By including this in the availability guarantee, it would appear that risks for system performance are being buried inside equipment operational characteristics that the O&M service provider would have to adhere to. For example, if the performance ratio value is based off of an inaccurate model choice (specification), or irradiance is lower than what the model predicts, then the availability calculation could be well under the agreed upon amounts despite the O&M contractor following contract-specified preventative and corrective maintenance strategies. This is one argument for having a separate availability and performance guarantee, as decisions made early in the project lifetime have a certain level of risk initially borne by the owner and EPC, though some of that is then passed on to the O&M provider that must 'work with what they are given' to ensure the highest degree of uptime for that system.

When including performance in the availability calculation, the performance ratio also appears to be a way to capture what could be considered "partial availability" or "partial performance states" where the equipment is operational, but in a degraded or "out of specification" manner. All PV equipment will degrade, though some components will degrade faster, speeding up the time to failure. This method of using performance in an availability calculation can potentially capture modules that are non-operational on the dc side as a way to tie the equipment and performance together in one metric. The real issue is that capturing a partial availability state due to degraded components is challenging based on the subjective nature of the measurements and an understanding of the degradation pathway. PV modules are well known in this regard as they have generally accepted degradation pathways that reduce performance to a degree that can be tracked. However, when the module degradation goes below that threshold, does it then become "unavailable" as it can be subject to a warranty claim? Or is it unavailable only when it can no longer produce energy? The sensors, instrumentation and physical models necessary to capture degradation pathways for the many components in a PV system have not yet been developed along with the cost-benefit analysis of tracking this degradation in a preventative or forensic manner. From the working group discussions, this issue has been one of the more difficult ones to address for the reasons stated above. Section 5.7.3 provides more discussion on the pros and cons of this approach, and its role in improving availability guarantee contract language.

4.2.3. Availability Guarantee and Definition

Only one guarantee was outlined with a formal definition. One could argue the definition is also reflected in the calculation of availability, which is compared to the "guaranteed" level for purposes of the contract. However, having a clear and accepted standard definition helps all parties to better understand the purpose of the guarantee. Consider the language from this contract:

> "'Availability' per the intent of ANSI/IEEE 762-1987…is defined as follows: Equipment is in an Unavailable state when the equipment is not capable of operation because of operational or equipment failures, external restrictions, testing, work being performed, or some adverse condition. The unavailable state persists until the unit is made available for operation by being synchronized to the system in service state."

This language uses the reliability/availability definition from IEEE 762 developed for traditional power plants and refers to the multiple pieces of equipment that allow the 'generating unit' to operate at its maximum capacity. With reference to a PV system, a generating unit could be defined, in this case, as the modules and balance of system connected to an inverter; however, this language is not clear and the definition does not account for the fuel source differences for PV. An update for PV plants would make the standard more relevant for large systems that could eventually be required to track and report on reliability metrics. IEEE 762 was revised in 2015 for wind turbine generation data, as an example (NERC, 2015).

Multiple O&M contracts provided by the working group had availability language in the contract, but without the accompanying availability guarantee. In these contracts, availability is defined as follows:

- "By way of example, if the System is capable of producing electricity, but is not producing electricity because weather is not conducive to solar generation, the system nonetheless would be available."
- "Guaranteed Availability means the amount of time that the Facility will be able to produce electricity when adequate solar resource is available."

These two definitions are clear that the solar resource must be available for tracking availability which is a necessary baseline for any availability guarantee. The first definition goes one step further in recognizing that the equipment can still be considered available to perform work when the resource (fuel) is not available.

The contractual availability guaranteed percentage reviewed in the O&M contracts ranges between 97% and 99%. This is the number that the calculated guarantee is compared to on an annual basis to determine if contractual obligations are being met. There was no language as to why certain numbers were chosen, though based on working group discussions, the earlier guarantees were likely lower due to reliability issues with early design and equipment and not having other PV systems to compare against when O&M agreements were being developed to service large PV systems.

4.2.4. Liquidated Damages

Generally following the availability guarantee are scenarios for liquidated damages that the O&M service provider will have to pay if the annual availability as measured is below a minimum or guaranteed amount as specified in the contract. In some contracts these are tiered based on the percentage below the guarantee. In most cases, the cap on damages is the total annual contract amount. Only one contract provided an availability bonus for meeting an annual target percentage. This up-side sharing may help incentivize maintenance improvements beyond meeting minimum requirements, and will be discussed below in the section on best practices.

The topic of liquidated damages is not covered here in terms of best practices; however, in many of the availability guarantees reviewed for this report, it is used as an opportunity to link the lost availability to a PPA rate or other revenue stream directly tied to the performance of the PV system. It follows that if the equipment is down for a certain amount of time and is not considered an “exception” (described in more detail below), the lost revenue as a result of that unavailability could be recovered by the system owner from the O&M service provider. Discussions with O&M providers participating in the working group revealed that liquidated damages are not a major issue for the PV systems they currently maintain, however they state that the fleet that is being managed is relatively young, primarily within 5 years of initial commissioning.

4.2.5. Contractual Availability Calculation

The mathematical representation of availability for the reviewed contracts and equations focuses primarily on how the equipment uptime and downtime is to be tracked. Four of the eight equations include performance in the availability calculation as a measure of available irradiance or performance ratio. Table 2 is organized in a way to show what degree PV system performance is included in that definition in the vertical direction, where equipment focused calculations are shown at the top (no inclusion of a performance ratio), and ones that are primarily performance focused are shown on the bottom (ones that do include a performance ratio). Definitions for acronyms and abbreviations used in the equations are shown at the right of the equations. There are additional calculations buried in some of the terms in both the numerator and denominator but are not shown here.

Analysis reveals that for equations that include performance, what is considered “availability” depends primarily on a measure of the amount of energy produced over the theoretical energy that could have been produced (considering measured irradiance) over a specific period of time, though not focused on the equipment state. This can be interpreted more as performance or energy availability instead of an equipment availability.

One equation included both the equipment states and tracking over time, and also added in expected and actual performance in the inverter availability calculation. Another equation looked at the energy generated, though explicitly tied to equipment events, including partial availability states (Hunt et al., 2015). This equation was not found in an availability guarantee, but included here as it represents internally how one company analyzes its utility-scale PV power plants and provides insight that can be used for industry best practices.

The remaining four equations are strictly equipment focused and generally follow the calculation of inverter uptime over the total time period, where the total time period is determined by the hours when the solar resource can essentially turn on the inverter (uptime plus downtime), and inverter uptime hours are those that count toward the contractual availability calculation, not factoring hours excluded in the contract.

Table 2. Reviewed Contractual Availability Calculations

		Equation	Definitions
Equipment Focused	**A**	$Avail.meas = \sum_{i=1}^{n} \frac{Avail.meas\ _i}{Total\ Inv}$	Avail = Availability Ei = energy Eff = effective Ext = external Hrs = hours Inv = inverters Irr = irradiance or irradiation Meas = measured Mo = month NP = nameplate Perf = performance Pot = potential Prod = production PR = performance ratio Unav. = unavailable
	B	$Avail = 1 - \frac{\sum_{Incident}(Inv\ Unav.Hrs\ \cdot \#\ of\ Unav.Inverters}{Total\ Inv.Prod\ Hrs\ \cdot Total\ \#\ Inverters}$	
	C	$Avail.meas = \frac{Inverter\ ON\ hours}{Avail.Window} \times 100$	
	D	$Avail = 1 - \left(\frac{1}{Total\ Pot.Prod.hrs\ \cdot NP\ Power\ All} \times \left(\sum_{Incident\ All} Total\ Unav.hrs\ \cdot NP\ Power - \sum_{Incident\ ext.cause} Ext.cause\ hrs\ \cdot NP\ Power\right)\right)$	
Equipment & Energy Performance	**E**	$Avail.eff = \frac{\sum_{i=1}^{Total\ Inv.} Inv.Avail.(\%)}{Total\ Inv.}$	

	F	$Avail.eff = \frac{Ei\ Generated}{Ei\ Generated + Ei\ Lost}$	
Energy Performance Focused	**G**	$Avail.meas = \frac{Ei\ Produced}{Theoretical\ Ei\ Produced} \times 100$	
	H	$Avail.level = \frac{Ei\ Produced}{Irr.\ \cdot Peak\ Capacity\ \cdot\ \overline{PR}\ 6mo.} \times 100$	

4.2.5.1. Calculation Step

Defined in the contractual availability calculation and sometimes in the contractual availability definition is the time frame and time-step for collecting data used in the calculation. The contract language time-step varied between 5 minutes, 15 minutes, 1 hour, and 7 days for collecting availability-level data. The contract with 7 days was interpreted more as energy availability and not equipment availability. Most contracts used either 15 minutes or 1 hour for the time-step.

The value used in the contract depends on the size of the PV system and setup of existing monitoring for items such as the performance guarantee. As to what is appropriate will have to be agreed upon between the contract holders as there are many other factors, such as calculation of renewable energy credits, and reliability reporting to state or federal agencies that may also define the fidelity of collected data. The discussion below on sufficient irradiance and PV system size can also drive the selection of a calculation time step.

4.2.6. Contractual Availability Window and Sufficient Irradiance

To know if an inverter is capable of producing energy from a basic equipment availability perspective (on or off), energy must be delivered from the module, through connections, junction boxes and disconnects. At the point where a sufficient irradiance threshold is met and energy can be sent to the grid, the clock starts for calculating the inverter uptime. For all of the contracts reviewed, the value varied between 50 W/m^2 to 100 W/m^2, with most in the 50 W/m^2 range. One contract suggested that the value be provided by the inverter manufacturer.

This metric helps remove times when different meteorological events can reduce the irradiance level low enough that the inverter fails to turn on. For example, this may include a significantly cloudy time period early or late in the day where the diffuse irradiance is not sufficient to turn on an inverter. See Fife et al. (2010) for more discussion.

Even more complicated is the fact that PV systems are installed in diverse locations with potential near and far shading obstructions. As PV systems increase in size and 'see' the horizon differently in different locations of the entire field, inverters will turn on and off at different times, depending on the position of the sun. Just having a statement that the clock starts when irradiance is 50 W/m^2 may distort the total operational time when measurement intervals are short and the time it takes for one inverter to turn on is longer than that time interval. This can also occur with a large PV system where, for example ½ of a field is shaded by clouds and the other ½ is not during early and late sun hours; if the irradiance sensor doesn't capture the shaded portion, the inverter availability clock may still be running even though there is not enough irradiance to keep the inverter on and delivering energy to the grid. If shading is inevitable in a particular location and irradiance drops below the threshold for a certain power block, an irradiance sensor that is not shaded in a different location may state that the power block should be accruing time, when in fact that part of the system is unavailable due to an obstruction.

4.2.7. Exceptions and Exclusions

Each contract reviewed revealed time periods where the availability clock stops for events that are not counted against the O&M provider. The language for these include exceptions, exclusions, excused availability, stopping periods, and external caused hours. These are important to compare and contrast as few contracts have the same exclusions, and some may have a large impact to contractual availability calculations. The following exclusions more common to the seven availability guarantees are as follows:

- **Interruptions due to grid disturbances and grid outages:** These generally are events where the PV system may be available to send energy to the grid, but the grid cannot take the energy. One contract even goes as far as to point out grid events that can trip the PV system inverters.
- **Owner/Customer interruptions, acts and omissions:** These exclusions cover events where the owner, either in writing, unilaterally or by omission, has the PV system stop producing energy. Whether intentional or not, each guarantee excludes any time stopped during one of these events in the availability calculation.
- **Force Majeure event:** Events that are beyond the control of the operator (O&M provider) and system owner, and include weather events that can cause damage, earthquakes, civil unrest, etc. Not every availability guarantee defines what constitutes a Force Majeure event as they are typically spelled out in the main O&M service agreement.
- **Manufacturer warranty:** Some, but not all of the contracts allow the availability clock to stop if a manufacturer warranty claim is necessary and made within a certain time window, if a part fails outside of the warranty, or the manufacturer is not honoring the warranty claim. In one contract, warranty repair does count against the availability clock after a 48 hour annual exclusion period. So, if the time to make a warranty claim and get product back into service plus other repairs that are not excluded add up to 48 hours in a year, those hours after the 48 excluded hours then count against the O&M provider. That

same contract states that if the O&M contractor is an affiliate of the EPC contractor who provided a warranty, then the availability clock does not stop.

- **O&M servicing for preventative and corrective maintenance**: In some contracts, performing O&M services, including preventative maintenance, thermal imaging and "subscription services" (outlined in the O&M contract) up to 48 hours, are excluded from the availability calculation. Other contracts do not exclude maintenance activities. Excluding some or all O&M services may have a large impact on the availability calculation, and likely forces certain activities to be done at night, or times during low irradiance when impacts to performance are minimal.

There are other exclusions that are not as common between each contract but are nonetheless important for this discussion. The other areas presented in the contract language include the following:

- Alarms and emergencies
- Theft and vandalism
- Performing non-subscription services for owner (outside of subscription services, and including response to Force Majeure events)
- Snow, ice and other obstructions
- Loss of system visibility through SCADA or DAS, if responsibility is outside O&M service providers control

4.2.8. Other Availability Guarantees

The availability guarantee elements discussed in the following section were not found within the reviewed availability guarantees, but provided by working group members to share other aspects that may be in an O&M contract or availability guarantee, depending on the type of system and additional guarantees purchased by the PV system owner. PV modules generally do not fall into this category as manufacturers offer guarantees for performance, though currently not for uptime.[9]

[9] Despite not having an assigned uptime or availability, it is worth discussing PV modules and their role in an availability guarantee. Many of the types of PV module failures (see IEA, (2014) for a comprehensive characterization of failures) that impact performance are generally categorized by the O&M provider as a whole, where a preventative maintenance check of a subset of modules, or every module may find a small percentage of modules 'failing' or completely failed. Typically, they are not removed right away for a warranty claim or replacement unless there is a large performance drop or a safety issue. The lost production from the degraded or failed modules is generally accepted to a certain degree depending on the size of the PV system as the cost to replace immediately may outweigh the lost energy. The modules are then tracked until a threshold is reached and replacement and warranty claims then ensue. How this relates to the availability guarantee is as follows: PV modules have not been historically considered in the guarantee as the inverter was the location of measurement due to its serial location where any fault or failure greatly reduces energy produced. What has been tracked typically as lost production may eventually be also tracked through uptime as module level power electronics (MLPE) become more prevalent. Before, it was impossible to cost effectively monitor every module and whether it was working or not. With MLPE, availability could theoretically be tracked at each module and used as the basis for an availability calculation.

4.2.8.1. Inverter Availability Guarantee from Manufacturer

Inverter manufacturers offer uptime guarantees for their product as well as a guaranteed availability for that inverter as part of a service package. As the companies have data from many years of operation, they are able to take the mean time between failures and other reliability statistics to calculate an uptime guarantee with a set annual availability percentage. These uptime guarantees will cost more to the system owner if trying to attain a higher availability say from 97% to 99%. The manufacturer will pay an amount or accrue a credit for the owner if availably goes below that amount over a specified timeframe.

Exceptions to that calculation are not counted as downtime and are generally similar to what was listed in Section 4.2.7 including external grid events, maintenance that requires a shutdown of the inverters, and lack of DAS visibility.

This type of guarantee can change the focus of the O&M provider and the site-wide availability guarantee itself, where taking the focus off of the inverter can allow opportunities for more frequently monitoring other components and performing dc health scans on a larger percentage of the system. Another option may include having a separate availability guarantee for combiners, disconnects, or trackers if the monitoring equipment fidelity allows for it (See Section 5.3.2 for more detail).

4.2.8.2. Availability Guarantee for Trackers

Some PV systems employ trackers and in some cases, availability guarantees between the owner and O&M provider are focused on the uptime of the tracker (operating or not operating) where penalties are a function of either energy lost or a percentage of the contract amount. Others are focused on the amount of energy lost if the tracker is not operating or not tracking in an optimal manner.

One tracker manufacturer assessed by an independent engineer had an uptime of 99.99% uptime based on past experience with existing customers.[10] This is not a guarantee provided by the manufacturer, but a measure of uptime. This does not cover off-tracking events where energy is still being produced, but lower than expected.

[10] http://arraytechinc.com/wp-content/uploads/ATI-Reliability-Fact-Sheet.pdf

5. IMPROVEMENTS AND BEST PRACTICES

The review of availability guarantee language in O&M service agreements and multiple discussions with the working group members over the past year has revealed many gaps and changes needed to improve the contract language. Adopting these changes and improvements as best practices will result in clear language that more accurately conveys the reliability state of the PV system and reduces uncertainty surrounding the PV system's long-term health.

Figure 1 presents an outline for defining an equipment-focused availability that can be used for (1) tracking overall PV system health for gaining greater insight into equipment reliability over time, and (2) setting up conditions for a contractual availability. These details constitute best practices that are discussed below.

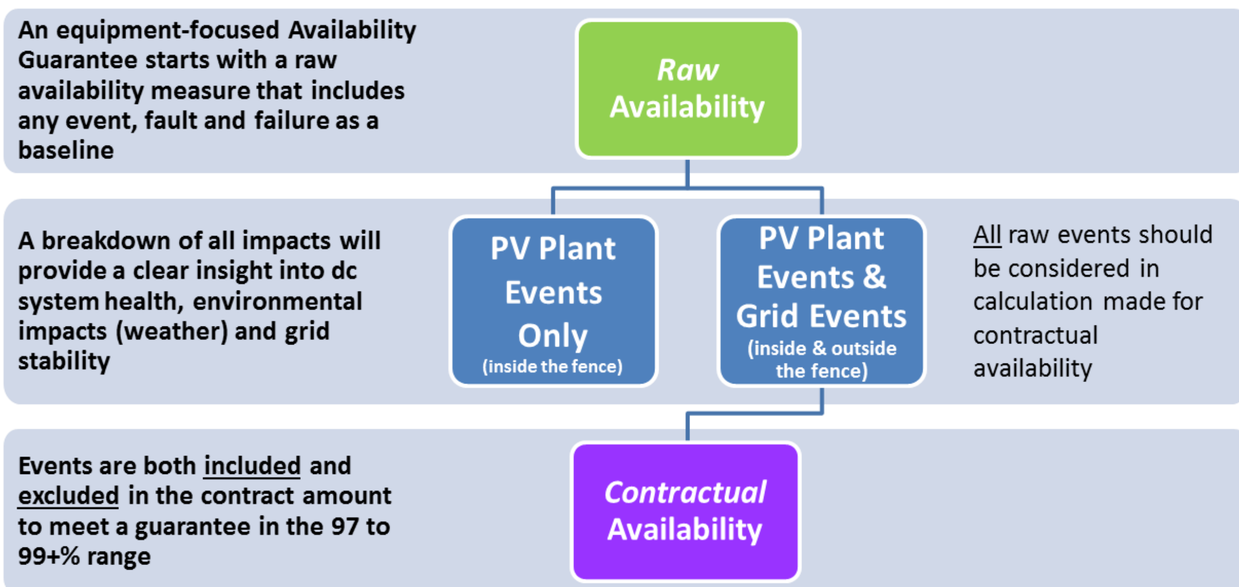

Figure 1. Best Practice Flowchart for Defining Equipment-Focused Availability

5.1. Availability as an Equipment Focused Metric

One area that stands out after reviewing the contracts and working group meeting notes is the issue of how to define "availability" in the context of a PV system. The use of availability and how it is defined depends a great deal on who the audience is for the metric. What PV plant owners may want to see from one plant or a large 'fleet' of plants will be entirely different than a project financier requiring a guaranteed revenue stream, or an O&M provider looking to provide services to meet an availability guarantee that is understandable and achievable.

5.1.1. Summary of Challenges from Contract Review

Looking back at the equations shown above in Table 2 that use performance metrics such as the performance ratio, one can see the weather-based and derate (e.g., soiling) uncertainty to the energy output of the PV system alongside the equipment operational state. Hence, these become 'energy' availability equations. A challenge when using a performance ratio is that the ratio can at times be greater than 1 due to model prediction error relative to measured energy output. This can misrepresent the equipment reliability states when used in an availability guarantee calculation.

As recognized by SunSpec (2014), "…performance is different than reliability although performance is dependent on reliability." Separating these key measurements allows for an O&M provider to focus on tracking equipment reliability over time and better understanding the true impacts to system performance from lost availability.[11] Dierauf et al. (2013) and SunSpec (2014) present many of these metrics and recently improved performance calculations that can better represent PV system performance as a function of different environmental conditions, which can reduce model and prediction error. These calculations, as well as methods from IEC 61724 (drawing from SunSpec (2014)) and IEC 62446 both currently under revision can be used to develop the calculations for performance guarantees, which as shown above in the contract review are often times linked to the availability guarantee when determining liquidated damages.

5.1.2. Best Practices

From a contractual standpoint, having a separate availability guarantee that is equipment-focused can be considered a best practice for the following reasons:

- The availability guarantee is the foundation for the performance of the system; therefore, an equipment focus can incentivize reliability-focused data collection. When availability is focused on whether the equipment is capable of performing its intended function, reliability growth and decline can be analyzed.
- Some inverter manufacturer availability guarantees are entirely equipment based. Tracking the equipment availability in a similar way will help owners and operators better track the equipment metrics to stay within warranty terms, and have the data necessary for a warranty claim.
- Performance data, such as a performance ratio included in an availability calculation may end up masking the equipment reliability state and make it difficult to respond to equipment issues when models are focused on kWh production. The modeled estimates used to calculate the performance ratio are made before the project is commissioned, and include uncertainty associated with soiling impacts, long-term climate and weather

[11] From an equipment perspective, the term 'available' or 'availability' for a full PV plant is an inadequate measure of energy production (the mission) because it may not be operating at full performance (rated energy production). The parallel nature of some inverter configurations may lead to situations where 9 out of 10 inverters (1MW each) are operating, so the plant is 100% available to produce electricity, but at a derated capacity (down from 10 MW to 9 MW) which results in reduced performance but intentional from a design perspective. This way of looking at availability works in certain industries where parallel configurations of equipment are considered backup; however, parallel inverters that are not considered to be on standby are central to meeting the energy production estimates resulting in an availability of 90%. For a plant with high dc overbuild, the 10th inverter may not always be necessary and having 9 out of 10 inverters operating (with one shut down intentionally or due to a fault) could still be 100% available from an energy perspective. If only an energy availability was measured or required and not a time-based availability, O&M activities may be delayed depending on when that inverter is needed.

uncertainty. Therefore, the performance ratio should be assessed within a separate performance guarantee and not in the availability guarantee.

- Separate tracking of availability and performance can then provide unique opportunities to see to what degree raw availability is correlated with performance, and where areas like soiling, expected energy or other factors have influence on that correlation.[12] Adoption of this comparative metric also allows for greater feedback potential to improve future projects while gauging the impact of anomalous faults and failures on the existing plant.
- In some cases, reductions in energy output do not often trigger a service call unless actual performance deviates 5 to 10% from modeled results. This is due to error in performance estimates (irradiance sensor, performance models) and reductions due to soiling and faults that may not impact performance as much in larger systems. An event that led to that power reduction may go undetected if availability is not measured at that location.
- It may result in more bids from O&M providers. Typically, O&M providers are looking to reduce risk when entering in an O&M contract that is typically a small fraction of the overall system capital cost. If O&M providers do not believe they are taking on an outsize portion of that risk, potentially more competitive offers will be available for the owner and asset manager to consider.
- An equipment-focused guarantee can potentially leave room for contract re-negotiation if issues in specific areas that are ‘tracked’ are discovered based on commissioning, degradation estimates, and PV performance model inputs.

5.2. Inverter & Grid Support Functionality

Most inverters currently deployed are typically providing active power to the transmission or distribution sides of the grid. Some of these inverters have the ability to provide frequency and reactive power support to help with load balancing and inductive loads. With the advent of California’s Rule 21 setting up the framework for inverters providing grid support functions, a look at how these functions impact system availability is necessary. Markets have not yet been developed to support these additional services from a large fleet of distributed generation inverters or large centralized independent PV system operators. Therefore, the incentive to operate outside of traditional active power generation in a way that impacts PV system availability has not yet been addressed.

A best practice for recognizing the current functionality of active power generation by existing PV systems is as follows: Any request by the grid operator to provide these advanced grid support functions outside of explicit recognition in an O&M contract should still view the PV system as available and ready to deliver electricity to the grid. For internal tracking, a separate

[12] If the PV performance model includes an availability calculation, and is tracked separately from performance, it is important that the model is changed to reflect 100% availability.

availability calculation could be calculated to encompass specific or all grid-induced events that prevent energy from being delivered to the grid. Due to the complexity of this issue, more research is warranted with regards to the raw and contractual availability impacts when utilities play a more active role in controlling how power is delivered to the grid.

5.3. Location of Measurement for Availability Calculation

This topic is important when determining what goes into an availability guarantee calculation. Typically, the component with the most events that result in lost power production has been the inverter, and earlier architectures that relied on single inverters were the focus of the availability guarantee as an outage at that inverter impacts the entire system's energy production. Recent PV system configurations have more parallel components, partially due to improved string-level maximum power point tracking technology, NEC code changes, and lower cost of monitoring equipment that can provide greater insight into dc health. These parallel configurations also improve the ability to plan service around outages that remove only a fraction of power production instead of the entire plant.

5.3.1. Irradiance Sensor Location – Daylight Threshold

The irradiance sensor's importance in calculating availability is that it can be used to determine at what point the contractual availability window starts during the day, which should correlate with when the inverter turns on. This threshold is typically specified by the inverter manufacturer, though there are other considerations that should be made when determining the daily start time for an availability calculation. Section 4.2.6 outlines the different times used in contracts reviewed for this paper.

The larger the PV system, the greater chance is that inverters in different locations will turn on at different times. Having irradiance sensors spatially distributed to capture that variation for large sites can provide insight into when far shading changes during the year, which may translate into one inverter turning on 15 minutes later than an inverter at a different location in the array.

Some PV performance models have the ability to model far shading. Taking irradiance output and inverter start times from the first modeled year of production and comparing it to actual production during that time should be done to refine the thresholds, if necessary. This is important if availability and performance modeling is done at a 15-minute time step or finer. Having the start time count against the O&M provider due to a poor understanding of irradiance thresholds can add up to a large amount of perceived downtime that could have been excluded if the irradiance thresholds for inverter operation were properly developed.

As will be discussed below in Section 5.7.2, the irradiance sensor can also be used to develop an irradiance weighted availability, which can better *prioritize* when specific preventative maintenance activities should be completed, and may be able to provide a greater correlation to impacts to expected energy production when outages occur at different times of the day; an outage early in the morning has much less financial impact in terms of revenue generation than one during the peak irradiance period. This can help prioritize O&M scheduling as for example, the potential for overtime labor to perform work during overnight hours may outweigh the benefits of lost availability and production compared to working on the system with normal labor hours during a cloudy day or during early and late hours with low irradiance.

Best Practice	• Obtaining irradiance threshold value from inverter manufacturer will provide a baseline value as to when availability clock should start. • Modeling and measuring irradiance levels at the site for a long period of time (a year) and comparing to inverter on and off times will improve the availability guarantee start and stop times due to the presence of far shading, plant size and other unique site characteristics. • Contracts allowing for adjustments to be made based on first year data, especially for sites that did not collect irradiance data before construction, will benefit all parties and improve availability measurements. • Utilizing an irradiance weighted availability calculation can help prioritize event characterization and response, and resulting impacts to energy production (Section 5.7.2).

5.3.2. SCADA and DAS Visibility

Working group members have stated that DAS/SCADA systems often have a large number of fault and failure events that reduce visibility of the PV system. This equipment plays an important role in the confidence of the data used to calculate the PV system availability, along with other parameters important for tracking system performance and electrical characteristics. If the DAS/SCADA is collecting data, though found to be not communicating, it would be considered an exception and not counted against the O&M provider as that data is stored in memory and can be downloaded when communication capabilities are restored. If the DAS/SCADA communication capabilities are down and is the responsibility of the O&M provider, then a prescribed amount of time should be set in the contract for the provider to fix the system.

Where outages start impacting availability depends on the level of detail where the availability is being monitored. If the DAS/SCADA system fails, is not collecting data and there are other locations in the system (such as the inverter or revenue grade meter) that can be used to backfill availability, then that information can be used in the availability calculations (if agreed upon by parties to the contract). In addition, if the DAS is not collecting data, and not fixed within a prescribed amount of time, the contract would need to include that downtime in the availability calculation.

Further, if the payment under a PPA or Solar Renewable Energy Credit (SREC) is tied to a DAS/SCADA, substituting another data source may not work under that contract and payment would be withheld. In that case, redundancy in the DAS/SCADA system would need to be considered.

Best Practice	• Develop availability guarantee language tied to specific component being measured (e.g., inverter) that recognizes data storage capabilities if SCADA or DAS is actively collecting data, but not communicating properly. • Delineate repair responsibilities to ensure that proper exclusions are made depending on who is contracted to repair the DAS or SCADA if it is not communicating, or has failed and not collecting data. • Development of a separate "DAS or SCADA availability" would help incentivize greater uptime of the monitoring and/or control system. This would be a separate calculation outside of recognizing the impact the SCADA or DAS system has on visibility of the equipment being tracked for the availability guarantee. • Allow for redundant measurement equipment and locations, with a hierarchy of data quality accepted in the O&M contract language that recognizes data collected from one sensor will be superior to others when calculating availability. An agreed upon method for estimating lost data will also be necessary.

5.3.3. Granularity - Boundary of Scope

The level of granularity for where to measure availability is extremely important as what is being used for satisfying the contractual availability guarantee may or may not be detailed enough to provide the right information to ensure the rest of the equipment is operating properly.

Capturing availability data on just 10 inverters in a large PV plant may miss equipment issues upstream that result in lost production. More granular monitoring provides greater and 'sooner' detail to improve response times, however other factors must also be considered. One working group member stated "*I would love to go lower than the inverter in a logical way. The sense of urgency to make repairs increases*."

Decisions on when to use different inverter, zone or string level monitoring depends a great deal on the cost of servicing the facility and the value of the electricity lost during an outage.[13] For example, systems that employ MLPE such as microinverters and ac modules provide even more fidelity when analyzing outages or when degradation reaches a 'tipping point' where it makes economic sense (and within O&M contract specifications) to replace individual modules.

Examples provided in Appendix A-1 provide insight into how faults located upstream and downstream of the availability measuring point can provide different results for dc and ac system health. In some cases, it may be advantageous to collect additional availability measurements at locations upstream of the equipment used for calculating the contractual availability value for the availability guarantee; failures or faults that are not readily identified and not counted against the availability guarantee (upstream of a central inverter, for example) may result in lower energy production that could potentially impact the performance relative to targets set forth in a performance guarantee.

If a new technology or manufacturer is being used and does not have a long track record or known reliability data, having a more detailed view of the modules, combiners, etc. may allow for improved response to potential early equipment wear out issues that would be covered by warranty or workmanship issues.

According to working group members, dc sensors now entering the marketplace have a low degree of accuracy. This is important when considering performance measurements, though availability measurements are primarily concerned with the equipment operational status. Leaving room for expert assessment of issues when reviewing data collected by dc sensors will be useful until data accuracy improves.

Best Practice	• The location of where to measure availability as well as which location is used for the availability guarantee should consider what information would be gained when looking at equipment impacts to lifetime system performance. • An analysis of potential quality, reliability and workmanship concerns should be done alongside an economic study including maintenance and servicing costs, as well as the value of lost energy, and the advantages and disadvantages of monitoring at different granularity levels.

[13] https://solarprofessional.com/articles/operations-maintenance/determining-optimal-pv-system-monitoring-granularity?v=disable_pagination

5.4. Force Majeure & Exclusions

The use of Force Majeure in O&M contracts and as applied to an availability guarantee is to recognize unforeseeable or foreseeable events that may adversely impact the PV system that are beyond the control of either party to the contract. This clause reduces the liability to the O&M provider in areas where certain events are considered the owner's responsibility and insurance products are purchased to cover the owner during a 'high risk, low probability' event.

Having a reporting period puts both parties on notice that a Force Majeure event took place, and stops the availability clock from the time the event started from the time the system is placed back into service. It is also a good practice that an independent third party be consulted if any dispute were to arise as to whether the event is considered Force Majeure or not, as well as disputes about workmanship issues that may have come up during a Force Majeure event. For example, one contract has a very high windspeed threshold to be considered a Force Majeure event. Lower windspeeds below that may still damage the system due to flying objects and uplift forces that may be attributed to poor design, installation or O&M practices. Therefore, avenues for disputes are necessary to determine when to stop the availability clock, or keep it going.

Force Majeure definitions in O&M contracts were found to extend beyond the typical catastrophic events, including environmental conditions that could for example, necessitate moving a tracking PV system into stow (tilting modules upwards to 0 degrees from horizontal) due to high winds. Much of this is for the protection of the system which then would not count against an O&M provider in terms of stopping the availability clock. In this case, the tracker would still be 'available' just not in an optimal position for harvesting the maximum amount of solar energy possible.[14] This can be categorized as severe or unusually severe weather to recognize that the wind event was outside of the design specifications of the PV system, but may not have arisen to the level of a tropical storm or hurricane. To reduce any uncertainty, specific storm categories should be reconciled with the plant design and wind speed measurements should be recorded onsite.

Grid outages or 'suspension' may also be considered a Force Majeure event if it is not caused by any party to the O&M contract and availability guarantee. These events, if not considered Force Majeure may also be listed as an excluded event for the purposes of the availability calculation. This outage may be caused by a natural disaster in one area that did not impact the PV system, but limits the ability of the grid to accept energy from the PV system. The PV system would still be available in terms of energy production, but not being able to deliver energy would not count against the O&M provider. This type of suspension would consider changes in legal and regulatory environments as well, where a curtailment would look like a grid outage as the PV

[14] This would only work if the system is designed to move into stow even when there is no power being generated by the plant. An engineered solution would need to have a backup source of power to allow for that movement so the equipment won't be damaged, or designed and constructed in such a way that if it cannot move into stow, it can withstand a certain magnitude and duration of windspeed before damage would occur and Force Majeure conditions would apply.

system is not able to delivery energy as promised under an interconnection agreement. It should be noted that these types of exceptions are listed outside of the standard Force Majeure language in some of the availability guarantees. Some working group members have suggested that Force Majeure should apply only to the catastrophic events, and other environmental and grid-related events should be tracked separately. This will need to be something agreed upon by the system owner and O&M provider.

Some contracts state that the O&M provider may be contracted to provide services in response to Force Majeure events outside of the main contact they operate under. If that O&M provider has the ability to offer that service, none of the time accrued during a Force Majeure event would count against that O&M provider.

Best Practice	• Force Majeure clauses in an O&M contract that cover catastrophic events damaging the PV system in a way that an insurance policy is necessary to cover the loss, or future regulatory environments that may prevent the PV system from delivering energy to the grid should be considered unavailable events that are not counted against the time accrued in an availability guarantee. • Contracting with the O&M provider to perform out of scope services as the result of a Force Majeure event may speed up the process due to their familiarity with that site, but would not count against the O&M provider while the site is not operational. • Whether to include exceptions outside of traditional Force Majeure clauses within the Force Majeure language should be determined by the owner and O&M provider. Clarity on events and thresholds for reduction of liability to either party should have a clear bar that is reached to reduce any uncertainty.

5.5. Warranty Considerations

How potential warranty claims (primarily for inverters and modules) impact availability is addressed in a few O&M contracts, and has been brought up by the O&M working group as an area that needs improvement.

The issue at hand is the timely servicing of the PV system. Some of the bigger challenges are the time it takes for parts delivery and a practice by some inverter manufacturers of allowing only in-house technicians perform warranty work. Responsiveness outside of an agreed upon timeframe in the contract may occur and impact both the uptime of the PV system as well as when the clock stops and re-starts for contractual availability. Working group members have also noted that it is necessary to document preventative maintenance activities that follow manufacturer recommendations to support a warranty claim. In the review of O&M contracts, there is language on how repair actions are handled as items outside of the contract if the manufacturer warranty expires during the contract period.

Many of the availability guarantees have exceptions for these issues where:

- The O&M provider is not held accountable for any of the time lost, and
- The O&M provider has a certain number of days until the issue has to be remedied where the clock will start again regardless of whether the part has been replaced or fixed.

It is entirely possible that some companies will go out of business and not be able to honor their warranties. Recent examples of this have not proved as dire as spare parts have been available for a certain inverter well after the manufacturer went bankrupt. However, it remains to be seen if this will play out with other manufacturers. Generally though, this may have an impact on how the availability guarantee is structured where servicing an item that now doesn't have a warranty, but did when the contract was entered into could result in longer wait time to get the system back on-line.

The timeframe for any partial or full shutdown could have a large impact on the system availability and trigger other contractual elements such as liquidated damages. As discussed above with Force Majeure situations, having an independent third party to evaluate technical issues during a dispute would be beneficial if an issue comes up where the warranty claim was denied due to alleged improper maintenance.

O&M providers do offer their own workmanship warranties, which appear to be in effect a year after the work was performed. It's not clear how workmanship warranties impact the availability start and stop times, however it more than likely any outage that is the result of the O&M provider's workmanship would not count as exclusion.

Best Practice	• A clear process for logging field data and response actions that may lead to an eventual warranty claim is needed, as well as a timeline for the owner and operator to agree upon. That language should be clear on what degree the O&M provider will help the owner. • Language should be developed to anticipate long-term warranty disputes and how the owner will respond if the manufacturer denies the claim. Impacts to the contractual availability calculation should be outlined in this scenario. • As the owner generally holds the warranty policy, lost time due to non-responsiveness by manufacturer should stop the contractual availability clock for the O&M provider until a solution is found. • When a warranty claim is not successful and equipment failure is

	due to lack of, or improper maintenance, then that downtime should be counted against the O&M provider in the contractual availability guarantee. • Have warranty response times offered by component manufacturer match the response times that impact the availability guarantee. • Workmanship warranties offered by the O&M provider should discuss contractual availability and exclusions. Any workmanship issues that are the fault of the O&M provider should not stop the availability clock.

5.6. Upside Sharing

The concept of sharing the upside of an availability guarantee was discussed multiple times in the O&M working group meetings. One availability guarantee had a bonus where the contractual availability had to be above 99.5% for that year, and the bonus paid out was a percentage of the amount over 99.5% and a percentage of the annual service fee.

As with any bonus for meeting or exceeding an agreed upon metric, in this case, the contractual availability, there would need to be funds made available to meet a specific payout. If the availability and performance end up higher than original financial estimates, those funds could potentially be appropriated for bonuses and made available from the additional revenue. Settlement periods could be set up every 2-3 years where gains in one year could offset losses in another, though still with a one year guarantee period where results are checked against.

As prices for PV systems decline and O&M budgets have been constrained (according to working group members) this could prove to be challenging. Also, the availability contract would need to be effectively high enough that an "industry standard" for availability is being exceeded. The 99.5% example from one contract was much higher than the range of availability guarantees reviewed and presented in Section 4.2.3.

Upside sharing could also be an important tool if raw availability were also to be tracked as part of the contract, where reducing the difference between the raw and contractual availability on an annual basis due to quick response times and good preventative maintenance may result in more energy produced. Doing so will also improve the system health throughout the contract life.

Despite these challenges, any upside sharing agreement would service both parties well if designed properly. The right combination of excluded and non-excluded events, along with a realistic contractual availability goal could have the potential to maintain both a high raw and contractual availability at the site.

Best Practice	• Ensure both parties are clear on the contractual language for upside sharing. Review for this metric would occur alongside review for uncovering any liquidated damages. • Provide example calculations to explain how the payout would work under certain scenarios.

5.7. Availability Equations

This section provides much of the detail for calculations used to define availability for use in an availability guarantee. These equations are used in scenarios presented in the Appendix that provide more context on different locations for measuring availability with some of the more common PV system configurations, and provide a basis for measuring availability for contract purposes. These base equations can be expanded into other definitions for performing reliability analysis or reporting site or fleet-wide reliability for regulatory purposes.

In the context of this paper, the availability definition should reflect the terms and conditions of the O&M contract and availability guarantee. Elements of reliability are discussed throughout this paper, and from an equipment standpoint, the definition should be able to differentiate the availability of the components that make up the system and how they define the overall system availability. Definitions presented in Section 4.2.3 from the contract review were scarce and mostly focused on the equation without a good description of why measuring and tracking availability is important. Hill et al. (2015) present definitions for component and system availability for use in an information model that can provide multiple metrics for different availability states that would be useful for grid operators evaluating reliability of large power plants. Those definitions are not only reliability-centric, but also serve to guide the definitions and equations presented here as high equipment up-time can be achieved only with a highly reliable system.

5.7.1. Raw Time-Based Availability

None of the contracts reviewed required calculation of a "raw" availability measurement as part of tracking the equipment reliability. Working group discussions have identified this as one area that would greatly improve the ability to assess PV system health and reliability over time.

The purpose for the raw availability measurement is to reveal the true condition, reliability and health of the equipment as events that are to be excluded in the contractual availability calculation, are not excluded in a raw availability calculation.[15] Trends in reliability, whether reliability "growth" or "decline" is occurring, can be better understood if raw availability is measured and calculated alongside the contractual availability over the PV system's lifetime.

Figure 2 below shows a hypothetical system where the contractual availability has fallen below the availability guarantee in 2 years out of 10, triggering liquidated damages. However, the raw availability has fallen under the availability guarantee 6 years out of 10. The graph reveals a decreasing availability trend that may not be easily discerned if raw availability is not being tracked. Now these raw availability numbers will likely reflect reduced performance over time and could be captured in a performance guarantee and potential liquidated damages scenario. However, if the link between reduced availability and performance is not made, the owner and

[15] This convention is the same as proposed changes to IEC 61724 where all down-time is excluded from the performance measurement and associated metric.

O&M provider may not realize the reliability decline and miss an opportunity to remediate the issue.

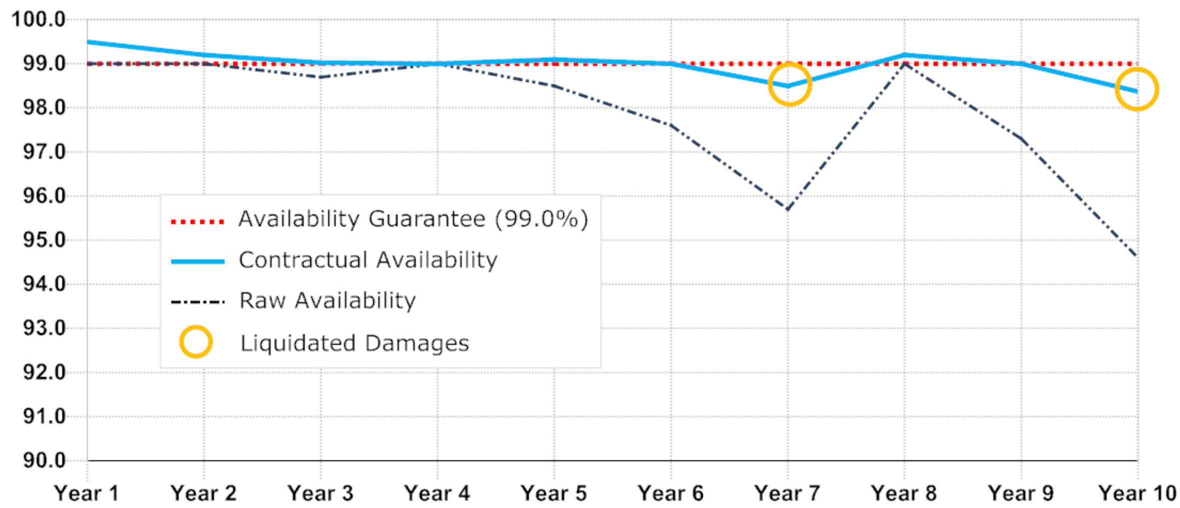

Figure 2. Comparison of a Hypothetical Raw and Contractual Availability to an Availability Guarantee over a 10-Year Period

Raw availability should be tracked because all availability guarantees reviewed for this paper generally *exclude* externally caused events by the grid. For grid disturbances where the equipment is available to delivery energy, though the grid is unavailable to accept it, a separate raw availability calculation that includes grid events would help differentiate internal and external impacts.

Raw Component Availability: This is the defined as *the fraction of a given operating period in which a component within a PV system is performing within the design specification,*[16,17] *with no exclusions*. This is similar to what is often considered "operational availability."[18] The given

[16] The term "design specification" for PV means "up to the point of producing energy, but excluding the amount of energy it is designed to produce." For a true picture of system health, even if design specifications necessitate preventative maintenance where the component is taken out of service, having that done when irradiance is below the inverter daylight irradiance threshold would be a recommended best practice. For a true raw system health, every instance of downtime, whether intentional or unintentional should be captured during the 'given operating period' which is the daylight irradiance threshold for when the inverter should turn on. Design specification can also cover whether the component is completely on or completely off, or operating in a highly degraded state, outside of what the manufacturer warrants, or recommends. Section 5.7.3 presents different scenarios on availability where equipment is operating in a highly degraded state, which may be classified as out of design specification. Some design specifications for inverters allow operation at high dc to ac ratios, which introduces clipping of dc energy input relative to a lower ac energy output.

[17] Hill et al. (2015) describes the following, which for this paper is defined below as the "Raw System Availability." "An average component availability term might be useful when addressing a system with multiple components of the same equipment, like average availability or the average of the sum of the individual like components. Practically, the component would be specified in the term to be 'average inverter availability' or 'average module availability.'"

[18] See http://www.weibull.com/hotwire/issue79/relbasics79.htm for a discussion of different availability calculations and definitions. Equations presented in this link require more information on the system reliability states, although many can be developed by segmenting the downtime of different components in order to calculate the MTBF and MTTR.

operating period for PV systems without energy storage is the time from sunup to sundown where site-specific conditions due to seasonality, near and far shading, and inverter operational thresholds are factored in (See Section 4.2.6 for more discussion). The component can be an inverter, disconnect, junction box, combiner box, or ac module, depending on the level of detail necessary to assess the reliability of the PV system.[19] Availability guarantees are typically focused on the inverter, however as dc configurations change with string inverters and ac modules, the location of the measurement needs to be carefully considered to ensure the measurement goals align with the fidelity of the preventative maintenance schedule, the availability guarantee contract target, and consideration of more frequent monitoring due to components that are known to fault or fail more often.

A simple time-based calculation incorporates elements of downtime along with the total operational time.

$$A_{raw\_i} = 1 - \frac{DownTime_i}{TotalTime_i} \qquad \text{Eq. 1}$$

Where:

A_{raw_i} = The raw availability of component i over a designated time interval.

$DownTime_i$ = the downtime (unavailable time) of component i over a designated time interval (15 min., 30 min., hour).

$TotalTime_i$ = the total time during the daily operating window (with sufficient irradiance) of component i over a designated time interval (15 min., 30 min., hour).

Availability within the selected time interval is generally tracked as either 0 (off), or 1 (on) to remove any ambiguity as to the equipment's operational state. Section 5.7.3 discusses situations where inputs to the equation can be modified for accounting for operational equipment, but in a highly degraded state.

Raw System Availability: *The sum of the components tracked in the availability guarantee are rolled up into a raw system-wide availability and can be used for comparing against the raw availability at the PV plant boundary to separate out any grid availability issues and contractual availability calculations.* The raw system availability typically represents the sum of all like components used to calculate the availability used for comparing against the availability guarantee value. Each component is weighted by the dc power that feeds into it. It is important that the total of the *same* components are measured when comparing to the contractual

[19] When calculating the component availability, choosing one component that can be best tied to energy production is suggested. For example, a 1 MW PV system with 250 kW inverter blocks may want to consider the availability measurement at the inverter, either on the dc or ac side, or availability at the combiner or sub-combiner level. For a system with ac modules or microinverters, the availability could be measured at each module if MLPE is available, and it can be tied more closely to energy production. The granularity would need to be determined based on the contract language and cost/benefit ratio of adding additional monitoring and the time it takes to collect and analyze that data (See Section 5.3.1 on measurement location).

availability guarantee. For example, if the contract states that availability is to be measured at the inverter, the raw system availability used to calculate the contractual availability (with exclusions) should be calculated only with inverter availability components. It may, however be useful to compare different component and sub-system availability measurements, (dc combiner, sub-combiner, etc.) the importance of which is described in more detail in Appendix A-1. The calculation for raw system availability is as follows:

$$A_{raw\_sys} = \frac{\sum_{i=1}^{n} A_{raw\_i} \times NP_i}{\sum_{i=1}^{n} NP_i} \qquad \text{Eq. 2}$$

Where:

A_{raw_sys} = the raw system availability of measured component over designated time intervals, for the designated time period (Typically over a year).

NP_i = the nameplate power associated upstream of component i, associated with A_{raw_i} when used in the numerator.

n = the number of like components (i) measured in the calculation (inverters, or combiners, or ac modules, etc.).

5.7.2. Irradiance-Weighted Raw Availability

As the raw availability calculation does not discriminate between an outage at 8:00 am under a low irradiance condition and the same outage at12:00 pm during a high irradiance condition, the relative impacts would appear the same. Therefore, the raw availability calculation as presented in Equations 1 and 2 can be modified to include irradiance for greater insight into the potential impacts to energy production when a certain piece of equipment is not operating. To be clear, this is not intended to be tied to performance as an “energy availability,” but based on the *potential* for energy output as a function of how much irradiance is available for conversion.

One working group member suggested that this would be an improvement to an equipment-centric, time-based availability calculation. Others see this similar to a performance ratio. Based on a review of availability guarantees for equipment only, none use irradiance weighting. In fact, it is primarily referenced for defining the “availability window” discussed above in Section 4.2.6. One availability calculation in Table 2 (see “H”) did include the use of measured irradiance; however it also included energy produced which embeds other losses and their associated uncertainties that may overlook non-functioning equipment that is not being measured by sensors.

The benefit of having an irradiance-weighted raw availability is that it helps track and incentivize when to perform services. When looking to establish a baseline for an availability guarantee, tying the availability calculation to irradiance can improve maintenance strategies developed for the O&M contract and incentivize both proactive approaches for preventative maintenance during low irradiance levels and response times for reactive servicing during high irradiance levels.

The example in Equation 3 is for one component for illustration purposes. The calculation presented here and outlined in Appendix A in more detail relies on the sum of irradiance for that day. As that value isn't known until the end of the day, the previous day's value could be used, or one calculated using a daily projection. For more accurate results, the annual measured sum should replace the estimated sum at the end of each day. An irradiance threshold should also be applied to remove time where the inverters may stop functioning due to low irradiance levels (Section 5.3.1).

$$A_{raw\_irr} = 1 - \sum \left(\frac{DownTime_{i\_irradiance}}{\sum irradiance} \right) \qquad \text{Eq. 3}$$

Where:

A_{raw_irr} = the raw irradiance-weighted availability for a specific component i over a designated time interval (day, for this example).

$DownTime_{i\_irradiance}$ = the irradiance value measured during component downtime (unavailable) over a designated sub-day time interval (hour, for this example).

$\Sigma irradiance$ = the sum of the irradiance over the sub-day time interval (day, for this example).

The summation of raw irradiance-weighted component availability into system availability can be done in a manner similar to Equation 2.

To show the difference for a similar component where irradiance-weighted availability is compared with an outage at different times of the day, and where raw component availability is compared to an irradiance-weighted raw availability, see Appendix A-2. These examples provide context for the impact of an outage if availability was tracked based on the potential for lost production.

Equation 3 has not been evaluated with a real dataset where raw availability from an operational availability guarantee was compared against the same guarantee, but with irradiance weighting. Studying the impacts over time with a real dataset will reveal where changes to PM, CM, sparing strategies and exclusions may need to be changed to reflect a more energy-focused impact in the availability guarantee. A study like this may also help shape to what degree performance guarantees are used side-by-side with availability guarantees. This method of tying equipment to the potential for generating energy may remove some of the risk to the O&M provider for taking on an additional performance guarantee with projected performance metrics that may include a large amount of error or faulty assumptions.

5.7.3. Partial Availability Discussion

The topic of partial availability is briefly presented here as it currently lacks real world examples on how to be handled for solar PV systems. This would apply as a 'raw' availability as a discussion on associated contractual elements is beyond the scope of this paper. If MLPE become more prevalent, and predictive inverter thermal models become standard, different ways of tracking and classifying availability can be considered. Based on the discussion above on whether equipment is available (1) or unavailable (0) for tracking on a time basis, the concept of partial availability has been discussed by the working group for situations where the component is operational, but in a highly degraded state outside of equipment specifications set by the manufacturer. Being able to track beyond just on and off would be an improvement as the health of the PV components can then be better tracked and assessed.

On the left side of Figure 3, PV modules are expected to degrade within an acceptable tolerance over their useful lifetime.[20] Degradation both inside and outside of normal tolerances is meant to be found during preventative maintenance checks, tracked over time and remediated through corrective maintenance actions before a certain percentage of modules fully fail, or are operating below the accepted tolerance. Once that degradation crosses into the unacceptable territory,[21] decisions need to be made. The question then becomes whether modules that are producing at less than the accepted tolerance should be classified as “unavailable” and grouped with modules that have completely failed, or should they be considered “partially available” and separated for tracking purposes in an availability guarantee?

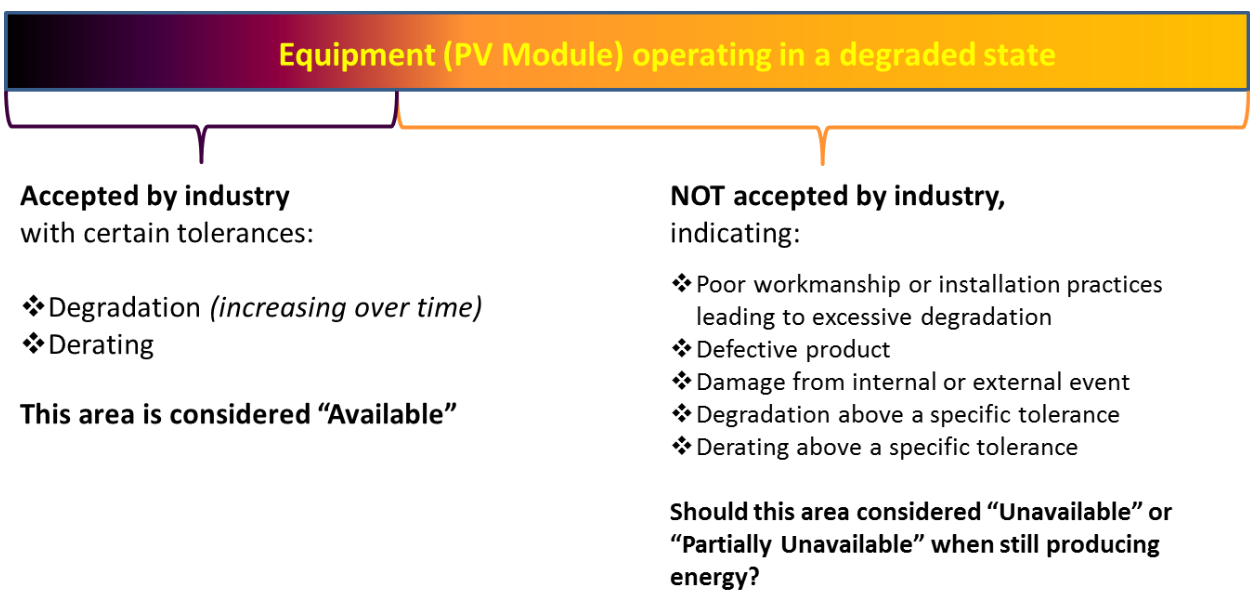

Figure 3. Availability Considerations for PV Module Operating in a Degraded State

The same question can be asked with regards to inverters that are operating at a reduced capacity outside of the manufacturer’s specification. How is an availability calculation performed in that

[20] This can also be referred to as an irrecoverable energy loss based on well-known device physics and degradation studies.

[21] These losses can also be referred to as a recoverable energy loss, which indicates that there is a failure mechanism that is reducing energy production more than accepted degradation. Recoverable losses due to failed equipment tend to be lumped in with the system performance. As PV system performance can be off by 5%, that uncertainty may mask the equipment failures that lead to reduced energy production and revenue generation.

situation?[22] A monitoring solution and predictive model that can track that degraded state would be necessary. The decision on availability would then be between the owner and O&M provider as to whether they consider operating out of specification amounts to a full failure, where it is unavailable for the sake of calculating the contractual availability, or agree on a "partial availability" calculation, which may be more difficult to define.

One approach is to define equipment that is operating in a highly degraded state as unavailable, which would mean that it should be scheduled for replacement or repair due to its adverse impacts on energy production. However, the threshold for how many modules should be replaced that are below the module performance warranty, for example, may differ between sites based on system size and related performance guarantees; if the highly degraded modules are still producing energy and the performance ratio or other performance test in the performance guarantee is not being impacted, then the highly degraded modules would be considered available.

Creating a fractional availability that can be measured over time, based on a calculation similar to Equation 1, is one approach suggested by the working group. It would need to be agreed upon however by the owner and O&M provider as to what that fraction would be for a module, inverter or other piece of equipment and the test procedure to capture that de-rated state. For example, an availability of 0.9 is assigned if an inverter is operating out of specification[23] where energy output is derated 10% over a specific time period. The benefit of capturing data in this manner is that it can provide more detail and trending that may lead to an early wear-out failure based on the design decision. From an O&M provider's perspective, this may warrant additional exclusions if the derating or degradation is the result of a poor design and installation decision, and not from an action by the O&M provider. In this way, if the out of specification condition is the result a design or maintenance issue, who bears that risk can then be negotiated by the owner and O&M provider as to whether those incidents and time lost is included or excluded in the performance guarantee.

However, if there is a performance guarantee in addition to the availability guarantee in the O&M contract, lost production due to the equipment operating out of specification can be captured. Therefore, creating a partial availability definition and calculation may not be necessary. Though capturing only the de-rated state in a performance guarantee may end up missing the events that could lead up to a failure event, and any lost production responsibility may end up being attributed to the wrong party.

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[22] The concept of dc overbuild may apply in this area if operating outside of normal bounds provided by the inverter manufacturer. However, some inverters are designed to operate in PV systems with high dc to ac ratios, but with manufacturer recommendations on what those limits should be.

[23] This derating would be above and beyond irradiance and ambient temperature impacts that inverters under normal operation already compensate for. This describes a situation where an external condition, poor design or installation, maintenance, or product defect can derate inverter output outside of the manufacturer specified operational window.

One can see how complicated the topic of defining and measuring partial availability can be, and how it is interpreted and implemented in an availability guarantee. Additional data, studies and modeling are necessary to better capture these condition states that lead to degraded performance, but are not easily discernable or known unlike what can be measured and predicted for PV modules.

5.7.4. Exclusions – Defining Contractual Availability

The base equations presented above can be modified to exclude time associated with particular events. How these exclusions are ultimately defined and added to availability guarantees and calculations is negotiated between the owner and O&M provider. Depending on how risk is to be accepted or offloaded, as the review in Section 4 shows, what is excluded in one contract may or may not be excluded in another.

Based on the premise of this paper that availability is an equipment-focused set of metrics and should focus on practices that improve the equipment reliability state, O&M providers may elect to negotiate for more exclusions if they end up accepting a contract that has a large degree of the resource forecasting and energy performance metrics embedded in the availability guarantee. Availability guarantees that end up separating out the equipment performance from the energy performance may result in fewer exclusions if the O&M provider believes the risk is adequately shared.

One area that may have a large impact going forward for exceptions in the availability guarantee is warranty repairs. Whether the industry will move towards component manufacturers offering O&M services, such as inverter manufacturers, depends on the level of service and pricing. In some cases, it will make economic sense to move the inverter availability to the manufacturer that offers an uptime guarantee. In others, it may not make logistical or economic sense to do so. Some inverter manufacturers may allow for warranty repair by qualified third-party technicians, with thorough documentation to ensure the integrity of the warranty. How these repairs are done within the warranty period will impact which exceptions are included in the guarantee.

The equation presented below provides a straightforward way to subtract out the exceptions from the raw availability calculation (Equation 1).

$$A_{exclude\_i} = 1 - \frac{DownTime_i - ExcludedTime_i}{TotalTime_i - ExcludedTime_i} \qquad \text{Eq. 4}$$

Where:

$A_{exclude\_i}$ = the adjusted availability considering excluded events for a specific component i over a designated time interval.

$ExcludedTime_i$ = the excluded downtime (unavailable time) of component i over a designated time interval (15 min., 30 min., hour). This includes Force Majeure and contractually excused unavailability events.

The excluded time is subtracted from the numerator to reduce the number of downtime time intervals (e.g., 15 min., 30 min., hour). The same excluded time is also subtracted from the denominator to reduce the total time. The excluded system availability, typically calculated over a year, can then be calculated using Equation 2, where $A_{exclude\_i}$ is used in pace of A_{raw_i}.

This method is consistent with a similar equation provided by a working group member that has reviewed availability guarantees and equations used in the PV industry. Comparing one scenario with both methods provides the same availability result.

A best practice would be to ensure that the excluded time is subtracted from both the numerator and denominator. In the validation scenario, if that time is *not* excluded from the denominator, the availability result is a little over 1% higher and grows as the percentage of excluded time compared to total time increases. To check this result, Equation "D" in Table 2 was used. In addition, entering similar results first into this equation assuming no exclusions, but including inverter nameplate capacity as required in this equation, yielded the same results for the method in Equation 1 and the method provided by the working group member (also with no exclusions).

6. UNDERSTANDING AND APPLYING AVAILABILITY GUARANTEE BEST PRACTICES

Based on the discussion presented above and feedback from the working group, a range of 'classes' is presented here for when to apply the different equations and measurement locations for future O&M contracts and availability guarantees.

This format was borrowed from, and modeled after the draft version of IEC 61724 (at the time of this publication) and their classification of monitoring systems, where the greatest precision, typically a larger and more complex PV system would require a higher degree of measurement and fall on the "A" end of the spectrum. Medium level systems requiring less monitoring than "A" would be classified as "B", and smaller systems requiring less precision of measurement would fall on the "C" end of the spectrum. This classification was also followed by Hill et al. (2015) for defining the type of information necessary for an availability information model, which provides a high-level view of data needs and reporting requirements for reporting on PV system reliability impacts to the grid. The reader is encouraged to look at the tables provided by Hill et al. (2015), which provide more detail about non-or partial-operating states for classifying events, faults and failures.

6.1. Contractual Availability Guarantee System Classification

The previous examples used for developing this type of table correlate the highest classification with utility-scale, and the lower classification for residential, or residential and small commercial scale. Generally, the data granularity would follow for the larger systems requiring more monitoring and smaller systems requiring less. However, this paper does not attempt to make those distinctions as there are different ownership models with single or fleet-wide portfolios, all with different PPA and interconnection agreements that may lead to equal sized systems requiring different levels of availability monitoring.

This classification also does not categorize the type or number of exclusions in an availability guarantee. All events are important for tracking the raw availability for better understanding equipment reliability and therefore should be included when stating which classification level is being used.

These measurement locations would be in the same place where existing performance measurements are made. If more detail on the reliability states of a certain type of equipment is needed, additional monitoring equipment should be installed for that equipment. In some cases, data collection may warrant that specific components are measured infrequently (based on a schedule or when an anomaly is detected) rather than continuously unless tied specifically to the availability guarantee in the O&M contract.

Table 3. Classification for Availability Measurements

Data Area/System Class	A	B	C
Data Granularity	**High**	**Medium**	**Low**
Components measured and potentially subject to availability calculation	Inverter, combiners (ac, dc), disconnects, modules, transformer, DAS, SCADA	Inverter, Combiners (dc), disconnects, DAS	Inverter
Necessary Instrumentation	DAS, SCADA, POA irradiance, Utility grade meter, inverter	DAS, SCADA, inverter, irradiance	DAS, inverter
Timestep	1 to 15 minutes	15 minutes	15 minutes
External Grid Events	Grid outage, curtailment, grid support	Grid outage, curtailment	Grid outage

Class A – This designation allows for the highest level of availability monitoring and would employ the use of backup or redundant devices for ensuring continuous data collection. This level may also cover what would be considered commercial systems with microinverters or ac modules where monitoring is available and the contract specifies detailed monitoring due to the presence of MLPE. If the system has MLPE, then availability and the associated guarantee can be calculated at the module level.

Calculating the availability of the DAS and SCADA equipment would be a component of measuring availability within this class as monitoring and control equipment is critical for accurate availability calculations in the system.

POA irradiance will ensure that more accurate inverter on/off times can be developed based on site characteristics and near/far shading.

Incorporating uncertainty into the availability calculation will improve the availability estimates. This is especially important with longer time steps. Also, when substituting primary data with secondary from backup sources such as other sensors or monitoring equipment, there may be uncertainty associated with that equipment and the resulting timestep and quality. Any uncertainty measurement should be expressed in terms of its relative impact to the final component and system availability value.

Class B – In Class B, many of the same components can be measured, though MLPE or string level monitoring may or may not be required or necessary based on the system configuration. More visibility on the dc side below the inverter will provide a better picture of dc health if monitoring under this class.

A lower accuracy irradiance sensor not in the POA may be able to provide enough information for looking at an irradiance-weighted availability or irradiance threshold. Satellite irradiance data may also be acceptable if the overall uncertainty is quantified and accepted in the contract. Any uncertainty measurement should be expressed in terms of its relative impact to the final component and system availability value.

Class C – This class generally covers residential and small commercial scale, but could also cover larger PV systems with one central inverter and where additional dc level monitoring is not part of a larger scope of services. A basic DAS system as part of the inverter may or may not communicate remotely, but would have the ability to store fault and production data to determine raw inverter-level equipment availability.

7. CONCLUSIONS

This paper presents a review of availability guarantees that have been used by the PV industry, intended to result in a high degree of equipment up-time, translating to performance and energy output that can meet or exceed financial projections.

Best practices are presented and discussed for improving the availability guarantee and definitions through better contract transparency, improving data transparency through raw availability measurements, and providing a framework for measuring raw availability at multiple locations, regardless of which piece of equipment is used for meeting the contractual demands. To make availability an equipment-focused metric, performance of the system needs to be separated in a way that respects how to track and measure equipment reliability, and also tracked so resulting performance impacts and benefits can be easily ascertained.

The ability to make more detailed measurements is a function not only of whether or not the site is instrumented in such a manner, but also of the site's ability to continue measuring data even if different components or the primary measurement system is not operable. Many working group members have stated that maintaining a high level of up-time for monitoring equipment is a challenge. Without the measurement capabilities, it will be difficult to accurately calculate availability for meeting contractual obligations.

Three areas that will require additional research for improved understanding from an availability perspective include: (1) PV systems with high dc to ac ratios, (2) PV systems with storage, and (3) PV systems with tracking technology.

High dc to ac ratios may have the effect of masking the performance impacts of degradation due to the 'buffer' that is built in for the plant's early stage lifetime. When compared to conventional PV systems with low dc to ac ratios, this buffer impacts O&M practices and the raw availability state of the PV system. Studying different scenarios from an equipment availability perspective and resulting energy produced is necessary to provide best practices for improved raw and contractual availability.

Energy storage devices can provide PV systems the ability to generate electricity outside of the traditional daytime operational hours, and also provide grid support services outside the boundary of the PV system. These new operational states will require greater study and scenario development that can build on the availability best practices presented in this paper.

The use of trackers provides greater energy harvesting benefits and introduces another piece of equipment that requires maintenance. How tracking operations impact overall system availability and what type of guarantee language should be applied to these systems will require additional outreach to industry on current best practices and areas for improvement.

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APPENDIX A: AVAILABILITY CALCULATION EXAMPLES

APPENDIX A-1 – RAW AVAILABILITY EXAMPLES

Central Inverters

For raw availability, A_{raw_i} the component level reliability can be tracked over any time period as long as the monitoring capabilities can adequately record the equipment operational state. If the monitoring equipment itself fails, then it will be difficult to record those values without backup monitoring. Traditionally, all availability measurements were just made at the inverter. As the most important failure point on most early centralized PV systems, the focus on inverter uptime was (and still is) a priority. Consolidated issues with performance could be measured on the dc side and ac side, and availability could easily be determined in terms of whether the inverter was on or off.

Due to lack of string-level monitoring, availability measurements of modules and combiners to transmit dc energy is more complicated for larger systems as the energy loss becomes less noticeable as the PV system increases in size, and pinpointing which string and combiner are not operating without real-time monitoring can be time consuming. Finding these failures/faults is generally done with IV curve measurements if a problem is suspected, or during preventative maintenance activities. Determining the time interval for how long that string or combiner was inoperable would be difficult at best.

In the figure presented below, a theoretical 16 kW PV system with 8 strings of 5 modules each, 4 dc combiners (4 kW each), 2 inverters, 1 ac combiner and 1 transformer illustrate the locations of raw component availability measurement locations. As this is a simplistic representation, it doesn't reflect every configuration (such as the inclusion of string or dc optimizers), nor is it intended to be electrically 'correct' from a design standpoint. The purpose is to show the importance of calculating raw availability at different locations in the system. To gauge PV system health, this hypothetical system is instrumented to be able to calculate raw availability at the dc combiner box, inverter, ac combiner and the transformer. Equations 1 and 2, introduced in Section 5.7.1, are used to calculate the component and system availbility, respectively.

$$A_{raw\_i} = 1 - \frac{DownTime_i}{TotalTime_i} \qquad \text{Eq. 1}$$

$$A_{raw\_sys} = \frac{\sum_{i=1}^{n} A_{raw\_i} \times NP_i}{\sum_{i=1}^{n} NP_i} \qquad \text{Eq. 2}$$

Each group of similar components can be measured together for an annual raw system availability, A_{raw_sys}. Using Equations 1 and 2, also presented in Section 5.7.1, the annual raw *system* availability calculated from the annual raw *component* availability for components in the figure below is as follows:

- dc combiners: 96.9%
- Inverters: 99%
- ac combiner: 100%
- Transformer: 100%

The assumption here is that one dc combiner is down 12.3% of the time, and one inverter is down 2% of the time over an annual period. The dc combiners have a lower system availability of 96.9% while the raw inverter availability is 99%. The lower dc combiner availability suggests that problems at the combiner level are reducing power delivered to the inverter (e.g., disconnect trips or catastrophic failure)[24] that can reduce the equipment availability. However for this example, combiner outages do not impact the inverter availability, which was much higher. As the system availability is weighted to the nameplate of the component, if the same 16 kW system was reconfigured, so the nameplate for inverter 1 was higher (at 12 kW) and inverter 2 (at 4 kW instead of 8 kW each for the example above) and combiner 1 and 2 were 6 kW each (with 3 and 4 at 2 kW each), the resulting system availability would result in a lower dc combiner value of 95.4%, and lower inverter value of 98.5%.

When comparing to an availability guarantee value, it is important to match the raw availability to the component used in the availability guarantee as stated in the contract. If the contract specifically states that availability is to be calculated at the inverter, then the inverter raw system availability would be the basis for making that comparison calculation and not a combination or average of the entire dc component availability. An owner and/or O&M service provider may want to track availability at a location upstream and downstream of the inverter if the O&M contract also has a performance guarantee with a high target value. As shown in this scenario, higher inverter availability may not correlate well with energy production in this scenario due to lower dc combiner availability. Tracking availability also at the dc combiner location would help distinguish issues with the modules or the combiner, whereas if it was just tracked at the inverter, determining the root cause may be more challenging.

[24] There are many types of dc combiner boxes on the market, some that incorporate disconnects, current monitoring, and arc-fault detection. As there can be many fused connections to multiple strings, if one fuse trips, that string is unavailable to deliver energy through the combiner to the inverter. Availability can be monitored at the fuse level, if that level of detail is desired; however, unless the fused disconnect is automatically tracked through a smart combiner box, accurately capturing the uptime and downtime for an availability calculation may not be possible. The inverter may also trip based on the threshold of power being delivered from both combiners. For this scenario, it is assumed that the inverter is still operable when dc combiner 1 is out. The discussion on string inverters below addresses some of the complexity with more parallel architecture that can better isolate faults and reduce impacts to equipment availability and system performance.

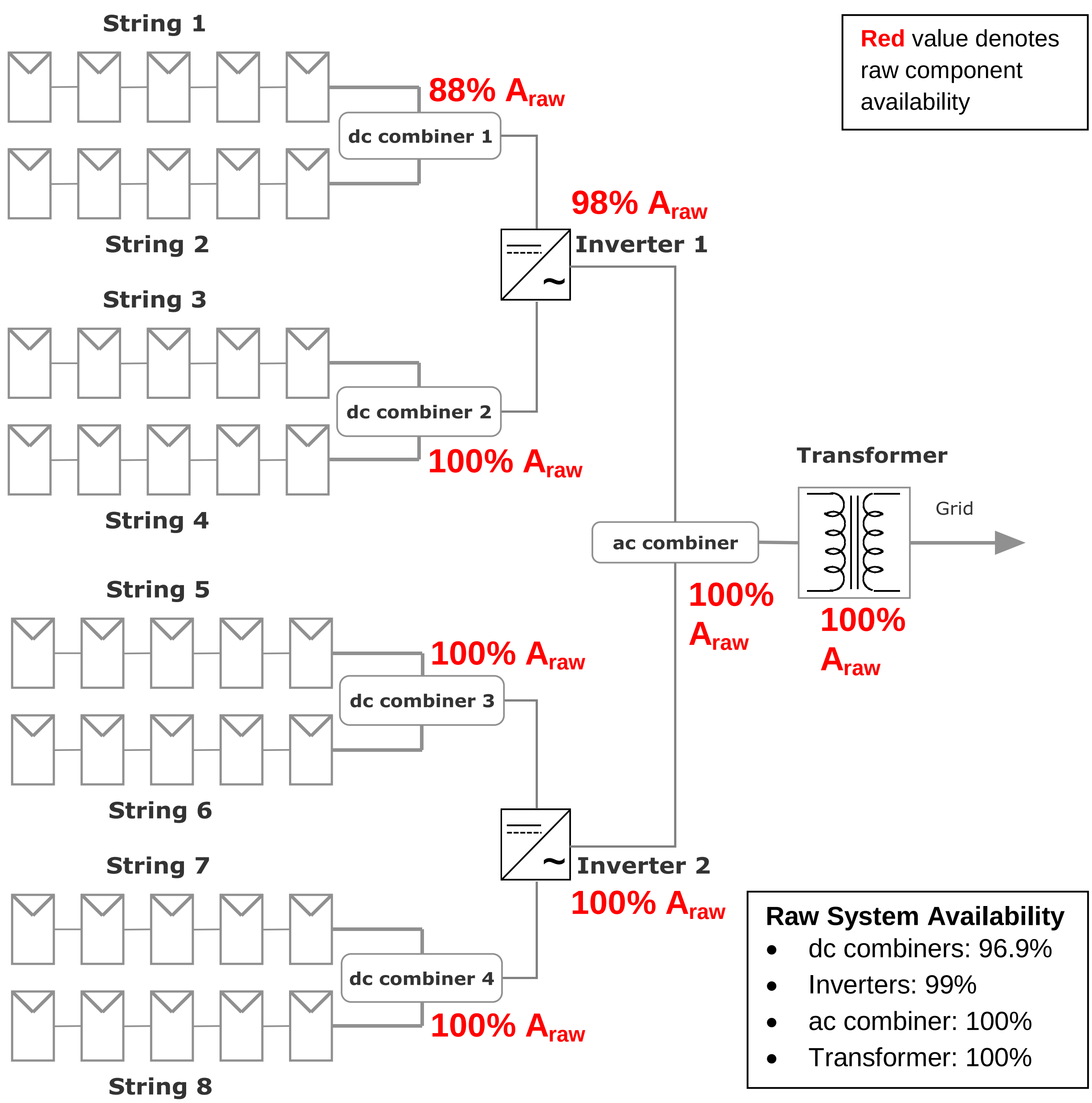


Figure A-1 – Central Inverter Availability Comparison

String Inverters

The use of string inverters is gaining in popularity for many Commercial & Industrial projects in the U.S. From an availability perspective, it provides greater fidelity for different 'zones' within the PV system, however there are many more measurements that must be collected, considering that a string inverter system may have 50 inverters for a comparable central inverter configuration with only two inverters. In the figure presented below, a 16 kW PV system with 8 strings of 5 modules each, 8 string inverters (4 kW each), 1 ac combiner and 1 transformer illustrate the raw component availability measurement locations. Instrumentation allows for availability to be measured at the inverter and at the disconnect on the single ac combiner. (A smart ac combiner box would have the ability to relay whether a string is on- or off-line, though in is the example with one string per inverter, it is assumed that monitoring is performed at the inverter.)

Even with string-level configurations that include monitoring, determining the availability state of a module cannot easily be done. Only ac modules, microinverters and some dc optimizers can easily track the module availability state.

Each group of components can be measured together for an annual raw system availability for that component, A_{raw_sys}. Using Equations 1 and 2 in Section 5.7.1, the annual raw availability for the different set of components is as follows:

- string inverters: 98.3%
- ac combiner: 95.2%
- Transformer: 100%

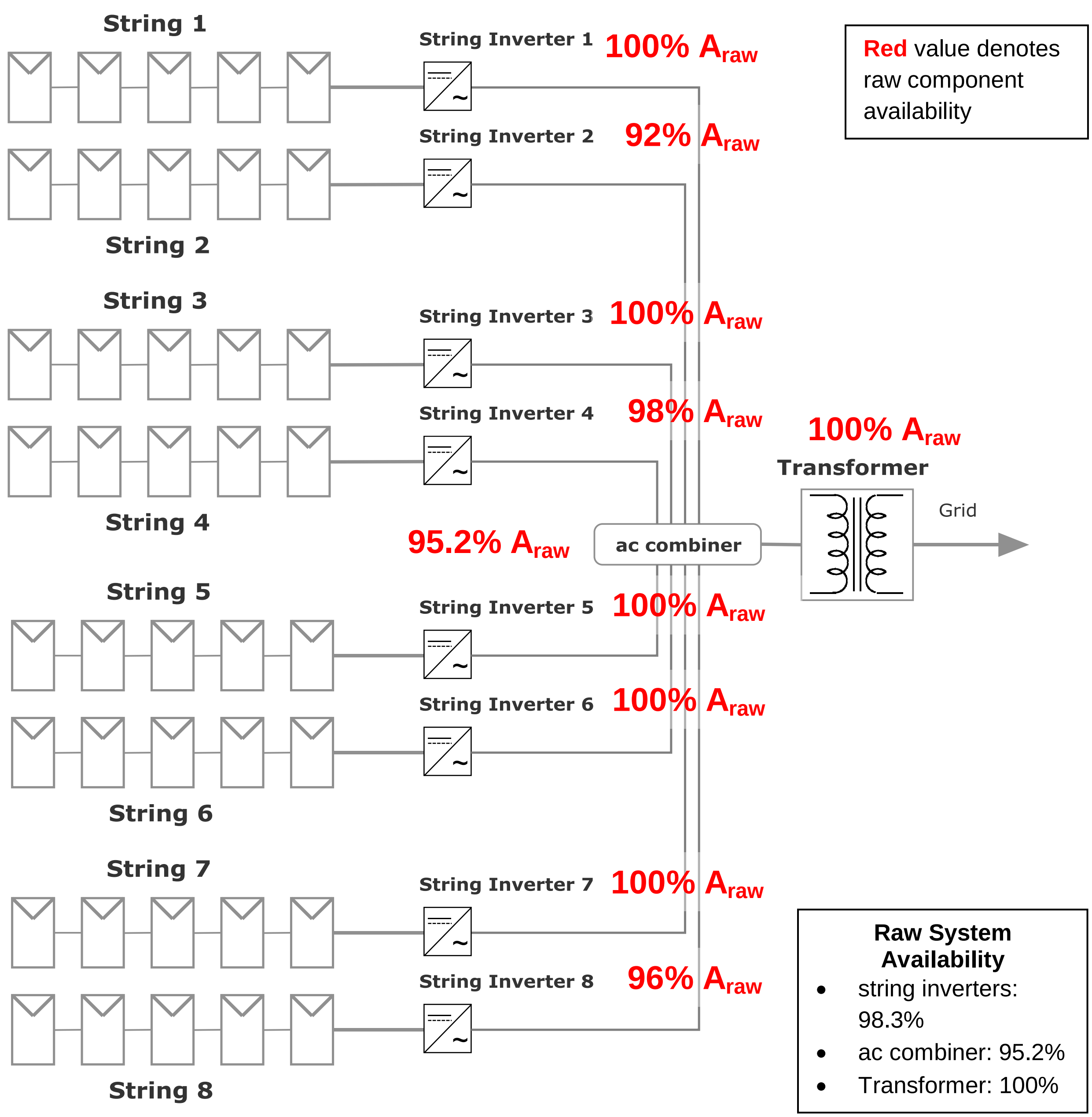


Figure A-2 – String Inverter Availability Comparison

For this example, any of the faults that impact the string inverter or ac combiner are assumed to be independent. The results reveal that on the dc side, with three string inverters having a 92% to 98% availability, the system availability of all 8 string inverters is 98.3%. In this case, there are issues with the ac combiner, where the availability over the measured time period is 95.2%, which is lower than the string inverter system availability of 98.3%. If, for example, a hypothetical contract stipulates that availability is to be measured only at each inverter, and with a combined guarantee of 98% for all of the inverters, then the guarantee was met. However, if the raw availability at the ac combiner was not measured, the larger contribution to lost energy from the 95% availability ac combiner box would be missed with a larger share of lost energy production potentially attributed to the inverters. Performance monitoring at each inverter compared to a sub or revenue grade meter would also pick up that discrepancy, though in a more complex system with multiple combiners and disconnects, determining the root cause of that energy loss would be difficult if the ac combiner availability is not tracked. This example, as well as the one above with central inverter architecture, reveals the importance of collecting raw availability at different locations than what would have been traditionally tracked with at the inverter for the availability guarantee.

Microinverter/AC Module

There are two different ways to look at the configuration of MLPE from a reliability standpoint. For microinverters, each module can be looked at independently of the inverter for tracking availability as long as the microinverter has the ability to differentiate faults and separate module failures from inverter failures. In the case of an ac module, the inverter is embedded in the module. So if the module or the inverter portion fails, the entire unit will be replaced. For this example, we assume for simplicity that the microinverter/module will be tracked the same as an ac module. The one challenge here is that if the microinverter fails, there is no simple way to know if the module is still working; however, for all intents and purposes, the module/microinverter combination is not available to deliver energy if just the module fails, or just the inverter fails.

For the example below, the microinverter/ac module availability is shown only if the availability is less than 100%. For Group 1, this applies to two modules/inverters and for Group 2, five modules/inverters. Each module is assumed to be 400 watts, equating to 9.6 kW per group. For simplicity, ac watts are assumed.

Each group of components can be measured together for an annual raw availability system availability for that component, A_{raw_sys}. Using Equations 1 and 2 in Section 5.7.1, the annual raw system availability for the different set of components is as follows:

- Microinverter/ac module: 99.1%
- Junction box: 100%
- Circuit breaker: 96%

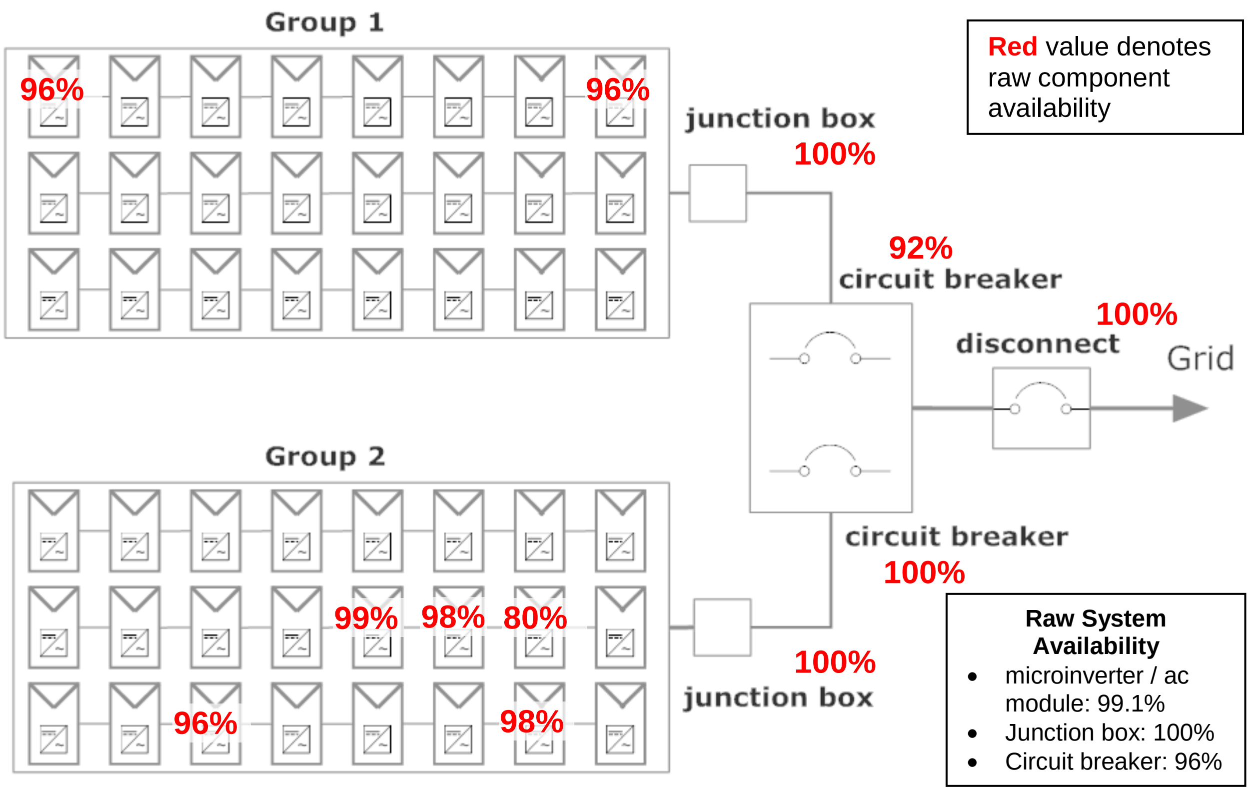


Figure A-3 – Microinverter/AC Module Availability Comparison

The microinverters, collectively (Group 1 and 2) have a high availability over the measured time period of 99.1%. In this hypothetical scenario, one circuit breaker is impacting the amount of ac energy that can be delivered by Group 1. Similar to the example above with string inverters, if availability is not measured downstream of the power production area, other BOS components can limit the amount of energy delivered; the degree at which that energy is lost due to that faulty component may be difficult to track if the equipment downtime isn't accurately captured.

This example shows how availability can be tracked for a system with a microinverter/ac module configuration. As the inverter is essentially with the module, it makes it somewhat easier to know if the module is operational though if the inverter goes out, additional testing would be necessary to know if the module also failed. The examples shown above for central and string inverters do not provide that level of fidelity, and inoperable modules may go undetected for a longer period of time in larger systems where module level diagnostic tools are deployed infrequently. As the power electronics for microinverters/ac modules allows for easily determining the operating state, an availability guarantee for these types of systems would likely be structured at the module level. This creates a large amount of data that will have to be tracked and stored. In some cases, if modules or microinverters are not working and the availability guarantee is not being impacted to where liquidated damages may result, the O&M provider may wait to replace the microinverter/ac module when other maintenance items are scheduled.

However, other components may cause disruptions and should be tracked for the reasons stated above.

APPENDIX B-1 – IRRADIANCE WEIGHTED RAW AVAILABILITY EXAMPLES

The calculation presented as Equation 3 in Section 5.7.2, and shown below draws from the raw availability calculation outlined in Appendix A-1, though takes it a step further by considering the relative impact of an outage that occurs at different irradiance thresholds; a 30-minute outage that occurs early in the day at low irradiance will have less impact on performance than a 30-minute outage that occurs during peak irradiance. This performance difference cannot be easily captured in a pure raw availability calculation (which is the basis for a reliability analysis) unless additional steps are made to correlate that outage to performance, which requires controlling for other losses and energy production assumptions. However when looking to establish a baseline for an availability guarantee, tying the availability calculation to irradiance can improve maintenance strategies developed for the O&M contract and incentivize both proactive approaches for preventative maintenance during low irradiance levels and response times for reactive servicing during high irradiance levels.

$$A_{raw\_irr} = 1 - \sum \left(\frac{DownTime_{i\_irradiance}}{\sum irradiance} \right) \qquad \text{Eq. 3}$$

For calculating the component downtime for irradiance-weighted availability, the event tracking is opposite of equation 1. Using 1 (off) for downtime and 0 (on) for uptime as the sum of the irradiance weighted downtime is calculated, and subtracted from unity.

It is important to note that use of this method requires the use of a pyranometer that is periodically cleaned and calibrated for determining site irradiance during the same time interval as the availability measurement. Having that pyranometer in the plane of the array greatly improves the accuracy. Using irradiance from a location other than the site in question or different time step could result in erroneous estimates. For example, a cloud can shade a large portion of the array locally including the on-site pyranometer, and when using pyranometer measurements from a site located 2 miles away as a proxy for the site in question, may miss that shading event. The relative quality of measurements and availability classes is discussed more in Table 3 in Section 6.1.

This equation would be most useful for larger or more complex systems where instrumentation is already in use for calculating certain performance metrics. Having an irradiance sensor would allow for this calculation to be made for a system that falls under Availability Class A and B (Table 3).

Outage - Time of Day Impact

To show the difference between outages at different times of the day, a daily irradiance profile with 15-minute measurements was used, with a 50 W/m^2 inverter ‘on’ threshold. A 30-minute inverter outage was simulated to occur early in the day as shown in Figure B-1a and later in the day during higher irradiance in Figure B-1b. To develop the irradiance-normalized availability for a single inverter, Equation 3 is used to determine the impact of lost irradiance during each 15-minute interval. Results reveal that a 30-minute outage earlier in the day equates to a 2.7% irradiance-weighted availability loss. An outage of the same duration later in the day results in a 6.3% loss. Different irradiance profiles will have a different impact on availability, with the example below showing impacts during a clear-sky day with maximum available irradiance. It is important to stress that this calculation is not using the performance of the PV system in terms of energy generated and delivered to the grid, as well as other metrics like performance ratio, etc. There are many other factors in the PV system that impact performance that are not directly related to the availability of the inverter as illustrated in Appendix A-1.

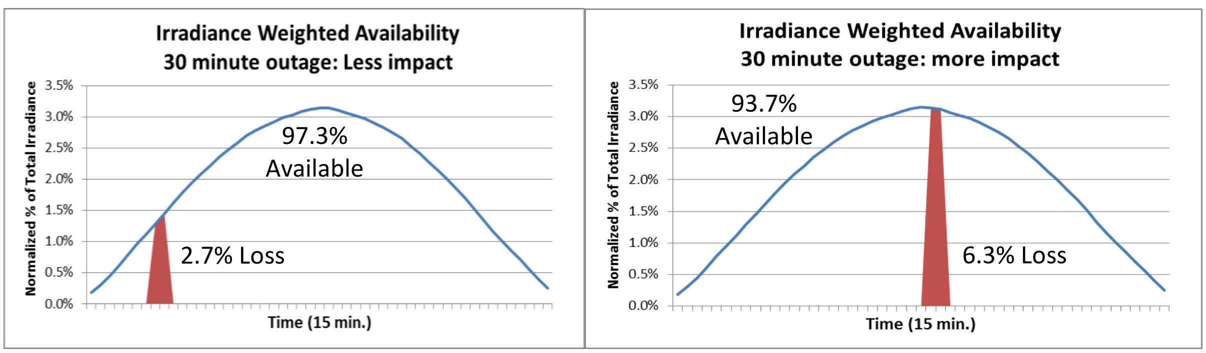
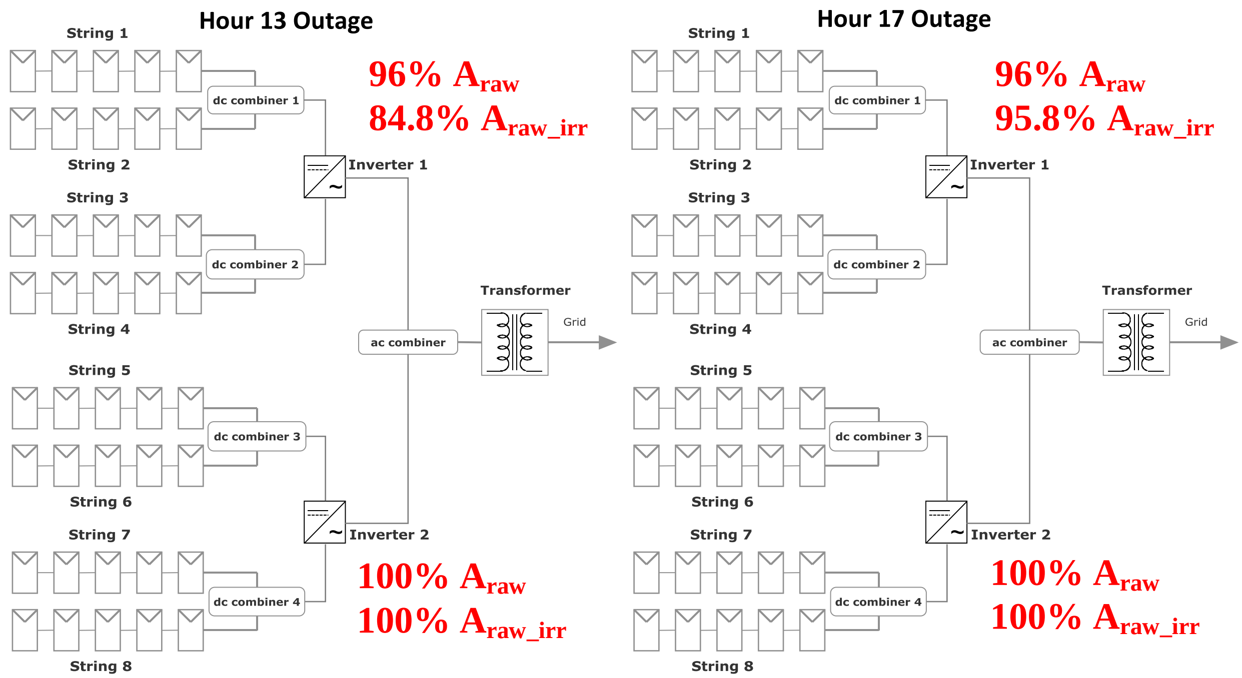


Figure B-1a (Left) and B-1b (Right) – Outage Comparisons for 1-Day Measurement of Irradiance Weighted Availability

Raw Availability vs. Irradiance Weighted Availability

To take this analysis one step further, a comparison of raw *component* availability to raw *component* availability with irradiance weighting is made. For this example, a synthetic hourly dataset of irradiance and outages is developed using Equation 1 to calculate the 1-day raw system availability and Equation 3 to calculate the 1-day irradiance weighted raw availability. The figure below shows a central inverter configuration with a one-hour inverter outage at hour 13 (left) and hour 17 (right) for Inverter 1 considering both availability measurements. The same layout is used as presented in Appendix A-1 for central inverters, where each inverter is 8 kW.



Hour 13 Outage			
	Raw Availability (Eq. 1)	Irradiance Weighted Raw Availability (Eq. 3)	Difference
Inverter 1	96%	84.8%	
Inverter 2	100%	100%	
Total Inverter Availability (Eq. 2)	98.0%	92.4%	**5.6%**

Hour 17 Outage		
Raw Availability (Eq. 1)	Irradiance Weighted Raw Availability (Eq. 3)	Difference
96%	95.8%	
100%	100%	
98.0%	97.9%	**0.1%**

Figure B-2 – Availability Differences for 1-Day Measurement of Irradiance Weighted Availability

Having the one-hour outage occur at Hour 13 results in 1-day 84.8% irradiance weighted raw availability compared to the 1-day 96% unweighted raw availability. The overall difference between the values, calculated using Equation 2 for sum of system level availability reveals an availability difference of 5.6%. If the one-hour outage occurs later in the day at hour 17, the 1-day irradiance weighted raw availability of 95.8% is much closer to the 1-day 96% unweighted raw availability with an availability difference of approximately 0.1%. The availability calculations are typically compared over a 1-year timeframe during the annual contract review, however for this example, only a daily availability is shown to illustrate the impacts when comparing to the daily irradiance profile.

This example provides a case for collecting irradiance weighted raw availability as not all outages are the same in terms of impacts to potential energy production. The caveat here is that the site would need to have the right instrumentation to capture the irradiance level at the same time interval as the availability measurement. If the owner and operator/O&M provider stand to gain from a more energy-focused analysis of availability, this option may help improve O&M practices from both a timing and cost perspective. Because this method requires more information and instrumentation, it would likely fall into the Availability Class A or B category of availability measurement details (Table 3). From this measurement, exclusions can be defined if it is to be evaluated as part of an availability guarantee.

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