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A framework for production availability studies for solar power

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Production availability analysis has long been instrumental for evaluations of production system performance in the oil and gas sector, supported by standards such as ISO 20815 on production assurance and reliability management. As the technical committee responsible for standardization in the field of the oil and gas industry, the ISO/TC67 have expanded its scope to include lower-carbon energy systems, making the applicability of ISO 20815 to renewable energy sources — particularly solar power — increasingly relevant. The main objective of this paper is to discuss the applicability of ISO 20815 for production availability analyses of such energy sources, where it examines how the framework defined in this standard can be used for large-scale photovoltaic (PV) plants. Key differences identified include high component counts, nonlinear relationships between irradiance and power output, strong temporal variability in environmental drivers, and challenges associated with large-scale aggregation and multistate degradation. A modelling approach based on Monte Carlo simulation is demonstrated through a generic example system, showing how PV plant production availability can be meaningfully assessed using planned production (per ISO 20815) aligned with expected energy (per IEC 61724).

Keywords: Production availability; production assurance; solar power; Monte Carlo simulation; standardization; ISO 20815.

1. Introduction

Production assurance studies, including production availability analyses, provide structured methods for quantifying expected production performance during conceptual and early-stage engineering. In the oil and gas industry, such studies have matured over several decades and are guided by ISO 20815 on production assurance and reliability management, which defines relevant performance concepts and modelling principles.

The global energy transition has led to an increased application of such analyses in renewable industries. Reflecting this development, the ISO/TC67 "*Oil and gas industries including lower carbon energy*" , being the technical committee responsible for this international standard, has expanded its mandate, now capturing specifically as part of the scope the lower-carbon energy systems, where the forthcoming third edition, currently represented by the ISO DIS 20815 (2025), incorporates applicability beyond its traditional oil, gas and petrochemical scope. This expansion creates a need to examine how well the existing framework transfers to new technologies and where adaptations are required.

Previous studies on wind power have shown that renewable energy systems differ fundamentally from petroleum production due to variability in resource input, nonlinear relations between environmental drivers and output, and the need for fine temporal resolution when estimating production losses. Solar power shares several of these characteristics, while also introducing new issues, including:

- Extremely high component counts at utility scale
- Strong diurnal and seasonal variation driven by deterministic and stochastic irradiance
- Interactions among loss mechanisms such as clipping, soiling, thermal effects, and inverter behavior
- Bidirectional energy flows when battery storage is included

This paper investigates these challenges, with an objective to discuss the applicability of ISO DIS 20815 (2025) for analyses of production availability of solar power systems. There is a practical modelling framework defined in this standard that can be used for such analyses, although it is not clear if it captures the solar power characteristics adequately. While the fundamental principles of reliability engineering might remain unchanged, there is a practical implementation for such systems that could differ in significant ways from traditional oil and gas applications. In this paper both the conceptual framework and the modelling approach are addressed.

The rest of this paper is structured as follows: Section 2 Describes how production availability for solar power is defined and should be calculated according to the ISO 20815 framework. Section 3 addresses some relevant modelling challenges as basis for the applicability of the modelling approaches discussed in Chapter 4. Section 5 gives some concluding remarks.

2. Definition and calculation of production availability

ISO DIS 20815 (2025) defines production availability as *"the ratio of production to planned production or other reference level over a specified time period"*. In the context of oil and gas installations, *planned production* is commonly derived from production profiles generated during field development studies. These profiles represent the maximum expected production under ideal operational conditions, constrained only by reservoir deliverability and process equipment capacities. Losses are understood as deviations from this planned production baseline, whether they are caused by equipment failure, maintenance, or operational restrictions. The standard provides a comprehensive taxonomy of production loss categories (given in ISO DIS 20815:2018, Table G.1); an established framework that has long been used to interpret the gap between planned and actual production.

When transferring these principles to solar power, the same definition remains valid, when compared with relevant international PV standards IEC TR 63292 (2020) and IEC TS 61724 (2016). However, the interpretation of *planned production* requires adaptation. Solar PV systems differ from petroleum facilities in that their production capacity is not governed by an engineered process with nominal capacities, but by the availability of a natural and highly variable resource: solar irradiance. Since irradiance fluctuates deterministically through day and night cycles, seasonally across the year, and stochastically due to cloud cover, the planned production of a solar plant must incorporate this natural variability from the outset. In other words, irradiance does not constitute an "unplanned loss", but defines the physical constraint under which all further production losses are evaluated.

This leads to a natural alignment between ISO 20815's concept of *planned production* and IEC 61724's concept of *expected energy*. In the IEC framework, the expected energy represents the energy a PV system would produce if all components operated ideally, given the actual or representative irradiance input for the time period in question. Energy Yield Assessments (EYA), standard practice in the PV industry, generate exactly this kind of profile by combining historical or typical meteorological irradiance data with system modelling of PV performance factors such as module efficiency, inverter characteristics, shading, and temperature effects. Using such profiles as *planned production* ensures conceptual consistency with the well-established methods of the oil and gas industry, while respecting the fundamentally different physical drivers of solar generation.

An important distinction must nevertheless be made. In oil and gas analyses, planned production profiles are often defined at coarse temporal resolution (monthly or yearly values), reflecting the relative smoothness of reservoir production behavior and the slow dynamics of process equipment. For solar PV, however, the temporal resolution of planned production must be sufficiently fine to capture the diurnal cycle and the non-linear transformation of irradiance into electrical power. Hourly resolution is generally necessary, while sub-hourly resolution may be beneficial for analyses involving battery storage or highly transient weather patterns. Finer temporal resolution has implications for simulation complexity, a topic discussed later, but it is essential for the faithful representation of solar resource variability in the planned production baseline.

The relationship between ISO DIS 20815 (2025) and IEC 61724 (2016) can be further clarified by examining the key PV performance indicators defined in the IEC standard. Some indicators, such as the capacity factor, are dominated by the inherent intermittency of sunlight and are therefore not meaningful as availability measures. Others, like the performance ratio, quantify the fraction of available irradiance converted into electrical output and thus reflect system efficiency rather than availability. Two IEC indicators are more relevant: the *energy availability* and the *all-in energy performance index*. Energy availability compares the actual energy to the expected energy under ideal technical conditions. This metric is directly analogous to production availability under ISO DIS 20815 (2025) when the expected energy is interpreted as planned production.

The all-in energy performance index, on the other hand, combines outages with degradation, soiling, thermal effects, clipping, and other factors that influence the conversion efficiency rather than the availability of components. Including these factors would break the intended parallel to oil and gas availability studies, which traditionally exclude gradual performance degradation unless it results in definable loss events. For this reason, adopting energy availability as the solar equivalent of production availability provides a clean and consistent transfer of concepts between industries.

It follows that the planned production of a solar plant must be described not only in terms of the energy expected, but also by specifying how it is derived: which irradiance dataset was used, at what temporal resolution, and whether degradation, soiling, or other long-term phenomena are included. As in oil and gas production availability studies, transparency regarding the assumptions embedded in the planned production baseline is essential for the interpretation and comparability of results.

In summary, production availability for solar PV can be defined and calculated within the ISO 20815 framework by interpreting *planned production* as the *expected energy* from an otherwise fully functional PV system under the actual or representative irradiance conditions. This preserves the fundamental intent of the standard while acknowledging the unique characteristics of solar resource dependence. The next section addresses the implications of this definition for modelling practice and highlights the challenges that arise when applying conventional production availability analysis methods to solar power systems.

3. Modelling challenges

Even when the definition of planned production is harmonized across petroleum and solar applications, the practical modelling of production availability for PV power plants introduces several challenges not encountered in conventional oil and gas production availability studies. These challenges arise from the scale of PV installations, the stochastic nature of the solar resource, nonlinear power conversion, and the limitations of existing software tools. This section outlines these challenges in detail, establishing the basis for the modelling approaches described in Section 4.

3.1. *High number of components counts and aggregation difficulties*

Large PV power plants may contain hundreds of thousands or even millions of modules. In principle, each module is a distinct production element with its own failure and repair behavior. Explicit modelling of such vast numbers of components is generally infeasible in production availability studies and conventional software tools due to structural limits and the computational load associated with discrete-event Monte Carlo simulation.

A common industrial shortcut is to aggregate many identical components into a single representative block with a combined failure rate. The simplest version assumes that the failure rates sum linearly:

$$\lambda_{\text{agg}} = n\lambda_m \qquad (1)$$

where n is the number of modules and λ_m is the failure rate of each module. This approach implicitly assumes independence, exponentially distributed failure times, and a negligible probability of simultaneous failures.

However, as the size of the aggregated block increases, the probability of multiple concurrent failures within a small-time interval is no longer negligible. The probability of two or more failures occurring within a time step $\Delta t$is given by:

$$P(N \geq 2) = 1 - e^{-n\lambda_m \Delta t}(1 + n\lambda_m \Delta t) \quad (2)$$

For large n, this probability grows significantly, reducing the accuracy of the aggregated exponential approximation. The result is that such aggregated components are, in reality, multistate systems, not binary ones. Whereas oil and gas systems typically consist of a manageable number of binary components with abrupt loss of function, PV plants require representations capable of capturing partial capacity loss and gradual degradation.

The use of k-of-n structures or Markov chains would be more appropriate for such systems, but most commercial software tools used for production availability analysis do not natively support these representations. This creates a fundamental mismatch between the nature of PV systems and the modelling capabilities available.

3.2. *Solar resource variability and nonlinear irradiance–power conversion*

In petroleum systems, production profiles are largely smooth and governed by engineered constraints. In contrast, PV production depends directly on solar irradiance, which varies continuously across multiple timescales due to predictable astronomical cycles and stochastic weather phenomena.

Furthermore, the electrical conversion process is strongly nonlinear. The current–voltage relationship of a PV module can be expressed as:

$$I = I_{\mathrm{ph}}(G) - I_0 \left(e^{\frac{qV}{nkT}} - 1\right) \quad (3)$$

where the photocurrent $I_{\mathrm{ph}}(G)$ depends on irradiance G. This nonlinear behaviour means that small changes in irradiance or temperature can cause disproportionately large changes in power output. When equipment failures occur, their impact depends heavily on the irradiance level at the time of failure. A failed string has negligible effect at night, modest effect on cloudy mornings, and potentially large effect under clear-sky peak irradiance conditions unless limited by inverter clipping.

Consequently, planned production profiles must have sufficiently high temporal resolution to reflect these dynamics, and production availability models must incorporate interactions between irradiance and component failures, which is rarely required in traditional oil and gas contexts.

3.3. *Solar resource variability and nonlinear irradiance–power conversion*

Discrete-event Monte Carlo simulation is the standard method for production availability analysis in the oil and gas industry. Simulation speeds are manageable because component counts are moderate and planned production profiles often use coarse time increments (e.g., monthly or yearly).

PV plants differ on both counts. Planned production profiles typically have hourly resolution or finer, and each change in irradiance generates a new event in the simulation. When combined with a large number of failure and repair events, the simulation event density increases dramatically.

Reducing the time resolution by averaging irradiance over long periods is not advisable because it distorts the nonlinear relationship between irradiance and power and eliminates essential day–night transitions. Thus, higher temporal resolution is necessary but significantly increases computational demands. This is one of the most important practical differences between solar and petroleum production availability modelling.

3.4. *Interactions among multiple loss mechanisms*

PV systems exhibit several interacting loss mechanisms, and this interaction complicates both the estimation and attribution of production losses in a production availability context. Unlike typical oil and gas installations, where loss categories are well established and tend to correspond to clearly identifiable failure events, PV systems contain overlapping phenomena that influence the mapping between system state and production output.

One prominent example is inverter clipping, which occurs when the DC power generated by the PV array exceeds the inverter's maximum AC conversion capacity. During such periods, additional DC power cannot be converted and is effectively 'clipped.' Because of this, the apparent impact of other loss mechanisms, especially soiling, may be partially or entirely masked.

When the inverter is already saturated, any further reduction in DC input caused by soiling does not translate to a measurable reduction in AC output. (Micheli et al., 2024) for instance, showed that inverter undersizing can conceal soiling losses during high-irradiance periods.

This phenomenon illustrates a broader challenge: the effect of any single loss mechanism cannot always be evaluated independently because the system response depends on its current operating point. Thermal derating, mismatch effects, or degradation may either amplify or reduce the visible impact of equipment failures depending on irradiance and system loading at the time of the event. These interactions highlight the difficulty of attributing production losses unambiguously and underscore the need for careful modelling choices in production availability studies.

Whereas production availability studies in the oil and gas industry have benefitted from a mature methodological culture that clarifies which loss mechanisms belong inside or outside availability calculations, the PV sector lacks similarly established norms. As a result, modelling practices can vary widely across organizations, and availability results may not be comparable without explicit documentation of how interactions among loss mechanisms were handled.

3.5. *Limitations of existing software tools*

Most software tools for production availability studies are designed for process industries such as oil and gas or more generic system availability analysis common in e.g. the nuclear industry. These tools assume binary component states, unidirectional flow and moderate component counts. PV systems violate many of these assumptions simultaneously.

PV modules and strings degrade partially rather than failing completely. Battery energy storage systems introduce bidirectional energy flow, which many simulation tools cannot represent natively. Large numbers of parallel components exceed structural modelling limits. And multistate capacity modelling is often unsupported or highly impractical.

These limitations do not prevent the performance of production availability analyses for solar plants, but they require significant adaptations such as aggregation strategies, surrogate modelling, or the use of external multistate models. These adaptations demand additional analytical skill compared to traditional ISO 20815 applications, and they illustrate the need for methodological refinement.

4. Performing production availability analysis for a solar power plant

This section outlines how production availability analysis may be conducted for a PV power plant within the ISO 20815 framework, as given in the ISO DIS 20815 (2025). Based on the main modelling challenges associated with PV and hybrid PV-battery systems, identified in Section 3, this section aim to clarify the practical modelling approaches that are proposed though this standard for such systems. The use is to be demonstrated through a generic example system. The goal is not to prescribe a single method, but rather to articulate a structured, standard-aligned process that accommodates the physical and statistical characteristics of PV systems.

4.1. *Establishing planned production profiles*

A production availability study begins with defining the *planned production*, i.e., the production level that would be achieved if all equipment operated ideally. For PV systems, this corresponds directly to the *expected energy* defined in IEC TS 61724-3 (2016). Planned production is typically obtained through Energy Yield Assessments (EYA), which combine:

- Historical or typical meteorological irradiance data,
- Site-specific shading and albedo conditions,
- PV module and inverter performance models,
- Temperature corrections, soiling assumptions, and design losses.

Whereas petroleum production profiles are often monthly or yearly, PV profiles must have sufficiently fine temporal resolution to capture the diurnal cycle and the nonlinear irradiance–power relationship. Sub-hourly resolution may be appropriate when analyzing PV–BESS interactions, but hourly resolution is usually adequate for production availability modelling.

To maintain consistency with ISO DIS 20815 (2025), the analyst must document the assumptions embedded in the planned production profile, including whether degradation or long-term losses are included. These choices influence the interpretation of availability results and their comparability across studies.

4.2. *Choosing the appropriate system decomposition and aggregation level*

After the planned production is established, the analyst must define the system architecture for the model. In ISO DIS 20815 (2025) analyses for oil and gas, equipment hierarchy is made with reference to the ISO 14224 (2016). For PV systems, IEC standards define PV components but do not prescribe a hierarchical reliability taxonomy. While IEC TS 61836 (2025) provides general PV terminology, the most relevant standards for defining hierarchical PV units are IEC 62548-1 (2023), which specifies PV array configuration, string and array definitions, and system topologies, and the IEC 61730 (2023) series, which formally defines the PV module as the certified functional unit. We can derive a natural decomposition thus: *Cell → Module → String → Array → PV Generator***.**

In principle, any of these levels could serve as the base modelling unit. However, modelling down to the module level is impractical for large PV plants. Even string-level modelling may exceed software limits when the number of strings is very large. Thus, aggregation is typically unavoidable. The choice of aggregation level involves balancing:

- **Accuracy**, which improves with lower-level modelling (more physical detail);
- **Computational tractability**, which improves with higher-level modelling;
- **Software capability**, which may restrict multistate or k-of-n representations;
- **Relevance**, which depends on which failures actually drive production losses.

Often, string-level modelling is feasible for medium-sized plants, whereas array-level modelling is preferable for very large facilities. Regardless of the choice, the analyst must ensure that the aggregated blocks still represent the key behaviors that influence production availability, particularly partial failures and multistate degradation.

4.3. *Representing multistate behavior*

Aggregation requires careful treatment of multistate behavior. As discussed earlier, the simplest aggregation technique—adding failure rates of individual components—assumes that the aggregated unit behaves as an exponential, binary-state component. Once the number of underlying components becomes large, this assumption breaks down.

There are three principal ways to represent multistate behaviour in aggregated PV blocks.

4.3.1. *k-of-n system representation*

An aggregated block consisting of n parallel modules or strings may be represented as a k-of-n system, where the block can deliver full capacity as long as at least k out of n subcomponents are functional. Each additional failure reduces incremental capacity. This representation captures partial degradation but requires software tools that support k-of-n logic with degradation or equivalent reliability structures.

4.3.2. *Markov chain formulation*

A more detailed representation uses a Markov chain, where each state corresponds to the number of functioning elements within the block. If failures and repairs follow exponential distributions, the transition rates between states can be expressed as:

$$\begin{gathered} q_{i \to i-1} = (n - i + 1)\, \lambda_m, \\ q_{i \to i+1} = i\, \mu_m, \end{gathered} \tag{4}$$

where i is the number of working elements, λ_m is the module failure rate, and μ_m is the repair rate. This model is accurate but seldom supported in standard commercial production availability modelling tools.

4.3.3. *Surrogate modelling of an aggregated block*

An increasingly practical approach is to construct a detailed model of a single array, including all modules, strings, and parallel groups. This can be simulated independently until the probability distribution of its power output is stable. This distribution is then approximated in coarser form (for instance, 5–10 discrete states with transition rates) and inserted into the full plant-level model. This method maintains some degree of accuracy while keeping the main model computationally manageable.

Each of these approaches has trade-offs. The final choice depends on software capability, plant size, data availability, and the analyst's experience.

4.4. *Modelling BESS within the production availability framework*

When a Battery Energy Storage System (BESS) is integrated with PV, the modelling complexity increases significantly. BESS introduces:

- **Bidirectional power flow**, which many software tools cannot represent natively;
- **Hierarchical component structure** (cell → module → rack → container → BESS) which adds to the high component count and aggregation challenges discussed in Sections 3.1 and 4.3;
- **State-of-charge (SoC) dependence**, which influences the system's ability to deliver or absorb energy;

Because PV–BESS systems can shift production in time, the interaction between the PV planned production and BESS operation must be clearly defined. In most production availability studies, BESS behaviour is modelled by:

- Charging whenever PV output exceeds grid-export limits,
- Discharging when PV output falls below a threshold,
- Prioritising load-shifting objectives consistent with the planned production profile.

The modelling objective remains the same, i.e., to estimate the difference between planned and actual production attributable to equipment failures and maintenance.

In practice, these operational rules for BESS modelling are often insufficient to capture the full impact of BESS-related failures on production availability. Because power can flow both into and out of the BESS, each failure mode may have asymmetric consequences depending on whether the system is charging or discharging at the time. For example, a converter failure during charging prevents surplus PV generation from being stored, while the same failure during discharging may directly reduce the energy available to meet the planned production profile. A taxonomy given in accordance with ISO 14224 (2016) can accommodate such distinctions, but only if failure modes and mechanisms are explicitly linked to operational states and directions of energy flow.

SoC dependence further complicates this modelling. The ability of a BESS to mitigate or reduce PV variability is strongly influenced by its SoC trajectory, which itself depends on the historical sequence of PV output, load, and failures. As a result, the production impact of a given component failure may vary significantly depending on the SoC level when the failure event occurs. To align with the ISO 14224 framework, analysts thus should define functional failures and degraded states in terms that reflect SoC-related limitations at the module, such as: "reduced charge acceptance," "inhibited discharge capability," or "capacity loss".

Incorporating bidirectional flow and SoC-dependent behavior typically requires either (i) an extension of the modelling framework to handle conditional energy-flow states, or (ii) a higher-level approach where the BESS is represented by a set of operational modes with associated availabilities. Both approaches should benefit from systematic hierarchical data collection per ISO 14224, to ensure that failures originating at lower levels can be traced upward to their effects on system-level charge and discharge functionality and thus to their influence on deviations from planned production.4.4

5. Concluding remarks

This paper has examined how the principles and methodology of ISO 20815 can be applied to large-scale PV power plants, including systems incorporating battery energy storage. Although ISO 20815 (2018) was developed primarily for the oil and gas industry, the underlying production assurance concepts, and the definition and calculation of production availability in particular, are sufficiently general to be transferred to solar applications when interpreted carefully. The key requirement is the alignment of *planned production* in the ISO framework with the *expected energy* used in IEC-based PV performance analysis. This alignment provides a consistent foundation for calculating production availability in a way that respects the fundamental characteristics of solar resource dependence.

At the same time, the practical implementation of production availability studies for PV plants differs substantially from established oil and gas practice. Solar systems exhibit extremely high component counts, strong nonlinear relationships between irradiance and power, multistate degradation rather than binary failures, and operational behavior that is tightly coupled to environmental conditions on short timescales. These characteristics make direct application of traditional production assurance calculation tools difficult without adaptation. In particular, large-scale PV installations require thoughtful aggregation strategies, careful handling of multistate behavior, and the use of planned production profiles with finer temporal resolution than is typical in petroleum studies.

Despite these challenges, this paper has shown that production availability analysis for solar plants is both feasible and meaningful when appropriate modelling techniques are applied. Aggregation methods allow analysts to capture the essential behavior of PV arrays without exceeding computational limits. Similarly, simplified capacity-state models enable effective representation of battery energy storage systems within the overall production availability framework. The example case demonstrates how these modelling choices can be combined into a coherent workflow that yields availability estimates suitable for concept selection, design comparison, and early-stage decision-making.

More broadly, the application of ISO 20815 to solar power highlights the ongoing evolution of production assurance practices as the global energy mix shifts toward lower-carbon sources. Whereas oil and gas modelling benefits from long-established conventions regarding the treatment of losses, degradation, and system boundaries, comparable norms are still emerging in the solar industry. As experience accumulates and standards continue to adapt, a more unified modelling culture is likely to develop, improving comparability and transparency across projects and technologies.

In conclusion, ISO 20815 provides a robust and adaptable framework for production availability analysis of PV systems, provided its concepts are interpreted in a way that reflects the unique characteristics of solar generation. With appropriate modelling adjustments, production availability studies can serve as a valuable tool for designing and evaluating the next generation of utility-scale solar power plants.

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