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Introduction

PV system designers and developers are tasked with the important decision of selecting the optimal Array-to-Inverter ratio for each inverter in a given project. The Array-to-Inverter ratio defines the relationship between the array's nameplate power rating at Standard Test Conditions (cell temp of 25ºC, irradiance of $1000W/m^2$, and Air-Mass 1.5) to the inverter's rated AC output power. As an example, a system with a 120kWdc array feeding a 100kWac inverter has an Array-to-Inverter Ratio of 1.2. The Array-to-Inverter Ratio is known by several names in the solar industry, including Oversizing Ratio, Overloading Ratio, and DC-AC Ratio. Until recent years, due to the high cost of modules, PV systems were designed with the aim of maximizing energy production per PV module. This approach typically resulted in oversizing ratios between 1.10 to 1.25 depending on the project location and design specific DC loss factors such as tilt angle, orientation, mounting method, DC wiring losses, mismatch, and soiling. With falling module prices, project financials have changed in favor of higher Array-to-Inverter ratios. The purpose of this article is to explain why systems are being oversized, the technical considerations relating to oversizing, and the impact of oversizing on the life of the inverter.

Why Oversize

Just a few short years ago, the main driver of system design was the high cost of PV modules. The goal of designers was to ensure maximum energy harvest from each PV module in the system. By doing so, designers ensured the optimal utilization of this high cost system component. Best design practices were to place modules to avoid shading from obstructions and between racking rows and to size the array to the largest capacity so the inverter spent little to no time power limiting. Power limiting is an inverter function that occurs when the available power from the array is greater than the inverter's rated input power. Power limiting is often called "clipping" due to the flattening effect on the system's daily production profile, as shown in Figure 1a.

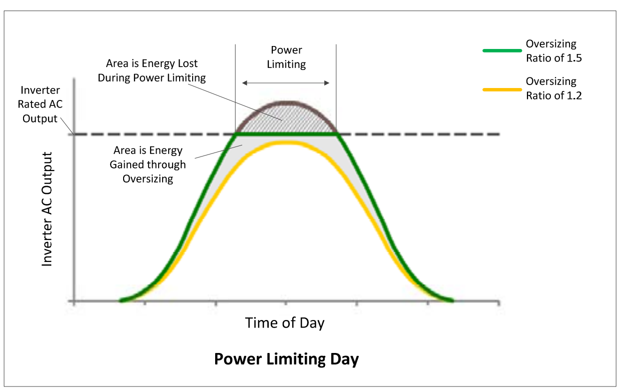

Figure 1a: Daily Production Profile
Power Limiting Day

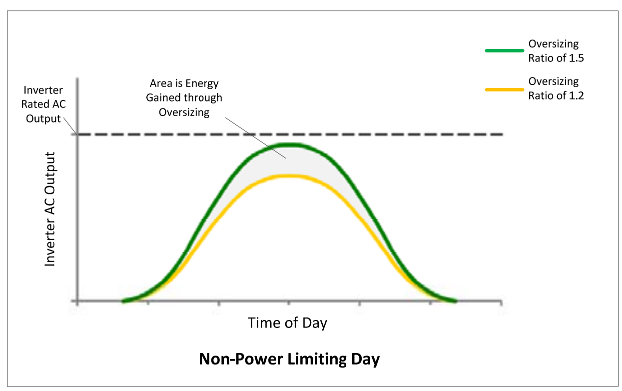

Figure 1b: Daily Production Profile
Non-Power Limiting Day

During power limiting, the inverter controls the input power from the array by shifting the array's operating point to a higher voltage and lower current operating point along the array's current-voltage (I-V) curve, thereby deviating from the maximum power point of the array. This is shown in Figure 2.

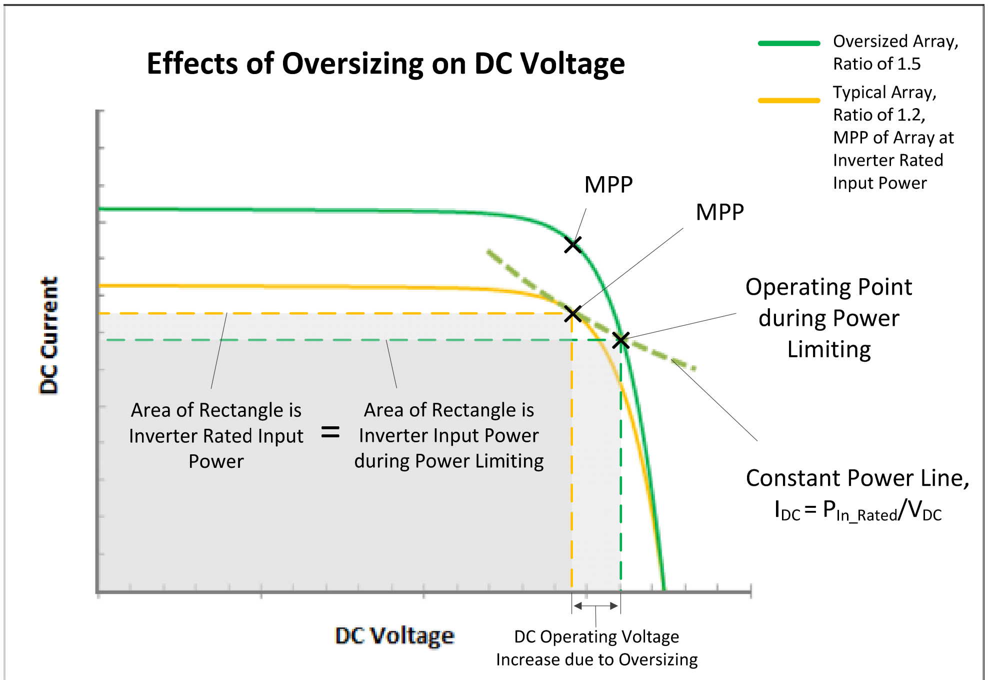

Figure 2: Array I-V Curves and Operating Points of Typical and Oversized Arrays

SIDE BAR:

A common question is whether the inverter diverts excess available power to an internal resistor bank to be dissipated as heat during power limiting. By controlling the operating point of the array, the excess available power is never made available to the inverter in the first place, but rather converted into heat in the array, resulting in less efficient power generation.

By maximizing production per module, designers achieve the optimal "specific yield" of the system. Specific yield is the system's annual energy harvest per kW of installed DC capacity. Specific yield is expressed in units of Annual kWh/kW. Optimizing specific yield typically results in Array-to-Inverter ratios ranging from 1.10 to 1.25, depending on project location and DC derating factors. **Figure 3** shows the effect of Array-to-Inverter Ratio on specific yield. As the ratio increases beyond a certain point, the specific yield begins to decrease. To optimize the specific yield of the systems shown here, the system designer should size the 10° tilt system at a ratio of approximately 1.25 and the 30° tilt system at approximately 1.15.

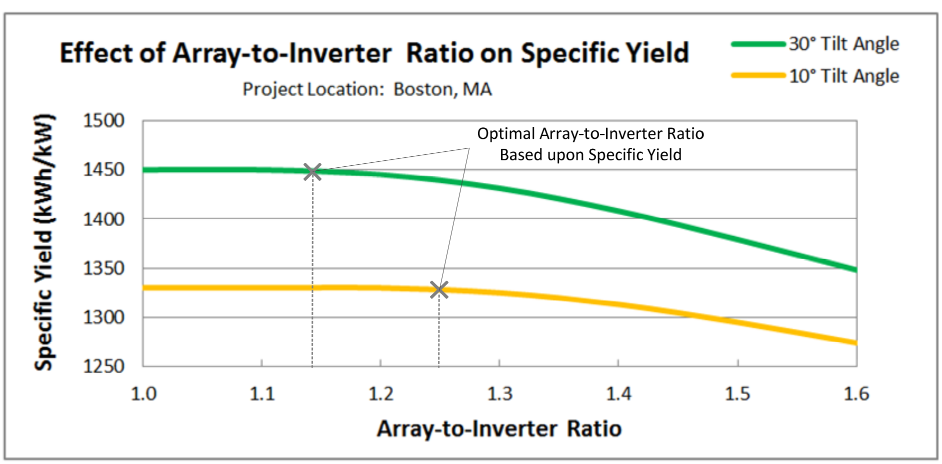

Figure 3: Effects of Array-to-Inverter Ratio on Specific Yield

With lower PV module prices, the incremental cost of adding additional DC capacity to a system has greatly decreased. Since a larger array feeding a fixed size inverter will result in greater system annual production, the increased annual energy harvest is spread across the system's fixed/semi-fixed costs, which include inverters, AC collection system, permitting, interconnection fees, engineering, and overhead. As a result, project financials have shifted in favor of increased Array-to-Inverter ratios. The scales tip even further in favor of oversizing when considering time-of-use (TOU) utility rate structures, which place the greatest monetary value for energy delivery in the afternoon during summer months. Through oversizing, systems produce greater energy when energy has the greatest value.

Oversizing due to fixed vs. incremental cost effect and the TOU effect has manifested in different ways throughout the industry. Increased oversizing is now being seen in large scale utility projects in the desert Southwest, with oversizing ratios over 1.5, as well as in space constrained commercial rooftop installations, where designers have begun encroaching into shaded regions of the roof. Commercial and utility systems alike are exploring impacts of reducing module tilt angle, decreasing inter-row separation, and reducing module cleaning schedules, all factors that result in non-optimal specific yield, with the aim of gaining increased annual production with the same fixed cost structure. Similar drivers exist in projects that are oversized to maximize production at sites with AC interconnection limitations.

To quantify the effects of oversizing, system designers perform an oversizing analysis using a PV system simulation program such as PVsyst, PV*SOL, or SAM. To be suitable for oversizing analysis, the simulation program must be capable of modeling the power limiting behavior of the inverter. Additionally, the program must be able to provide hourly data values when financial models are built on a time-of-use rate structures. In most cases, oversizing analysis is performed through successive simulations where the inverter size is kept constant while the array size is varied. The project team may also look at the effects of keeping the array size constant while varying the inverter kW rating. The end result is a dataset which shows the effects of Array-to-Inverter ratios on hourly and annual production.

The production values from the analysis are then fed into the financial model of the project to determine the optimal Array-to-Inverter ratio. The details of financial models will vary, but most have the same overall goal of optimizing a financial metric such as Levelized Cost of Energy (LCOE), Net Present Value (NPV), or Internal Rate of Return (IRR). An example oversizing financial analysis is shown in **Figure 4**. The analysis shows that oversizing improves the economics of a project up to a certain point; however, beyond that point, the project begins experiencing diminishing returns.

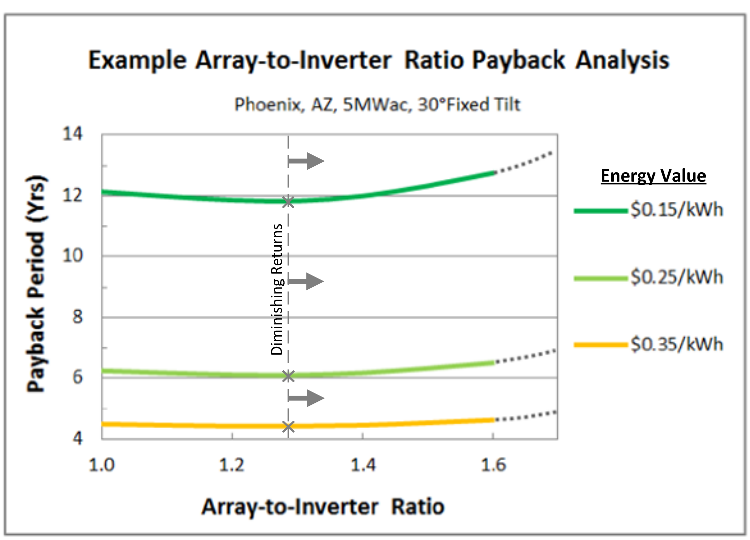

Figure 4: Example Oversizing Financial Analysis

SIDE BAR: OVERSIZING AND FINANCIAL RISK

There is debate in the solar industry about the ***level of accuracy*** of commercially available simulation programs. Each simulation program faces the same challenge of using historical weather data (often hourly values), system design information and loss assumptions to predict energy harvest. Uncertainty can arise from translating horizontal global irradiance into plane of array irradiance, estimating cell temperature from ambient temperature and wind speed, from questions of accuracy of the weather measurements (due to instrument calibration error and variation between site location and the weather station location), and from difficulty predicting losses due to soiling and snow, panel degradation, mismatch effects, inverter MPPT tracking efficiency, and effects of temperature and DC voltage on inverter efficiency. Many additional items could be added to this list. When combined with the fact that annual weather can vary from one year to the next, it is easy to see how uncertainty exists in annual energy production estimates. As these estimates feed the project's financial model, uncertainty in production estimates leads to investment risk. An oversized array helps to reduce annual production estimation risk by increasing the allowable margin of error on the DC side estimates during inverter power limiting.

Limiting Factors of Oversizing

Oversizing exposes the inverter to the following:

- Increased available power from the array
- Increased available short circuit current from the array
- Slightly increased full power input voltage during power limiting
- Increased operational hours at full power

Discussions up to this point have assumed that the inverter has power limiting capability, which is true of UL 1741 listed inverters. As part of listing to UL1741, an "Output Overload Test" is performed to confirm the inverter's ability to maintain rated output power when fed by a DC source equal to twice the inverter rated input current.

Although the inverter has the ability to control the current from the array during normal power conversion operation, during a DC side fault the inverter's capability to control the current from the array is through interruption *at best*. The scenario that subjects the inverter to the highest short circuit current is a low impedance fault ("bolted fault") within the inverter's DC section between the ungrounded and grounded circuitry or between ungrounded circuitry and ground. During these scenarios, the inverter is exposed to the full short circuit current of the array. The inverter's DC side componentry, including bus bars, cables, and switches, must be rated to carry and interrupt (in the case of electromechanical switches) the array's available short circuit current. The "weakest link" in this circuit dictates the maximum short circuit current that the inverter is rated to handle. Based upon the desired string count and string size, the maximum Array-to-Inverter ratio can then be determined. As an aside, this highlights the point that the maximum oversizing ratio of an inverter depends both on string count and string size.

Effect of Oversizing on Inverter Life

Designers, developers, and system owners should view the effects of oversizing on inverter life and Mean-Time-Between Failure (MTBF) through practical lenses. Large Array-to-Inverter ratios cause the inverter to work harder for longer hours, not only in the spring-time peaking hours, but also during the hotter summer months. In addition, most commercial three-phase inverters operate *less* efficiently when operating above the maximum power point voltage, resulting in greater internal heat rejection.

Common sense tells us that this can cause some of the temperature sensitive components to age faster compared to a lightly loaded scenario.

The good news is that inverters have thermal management architectures to control internal temperatures to protect the inverter during prolonged period of full power operations. These measures also act to help preserve the life of temperature sensitive components. Inverters sense temperatures of critical components and have programmed set points that trigger increased blower fan speed and power limiting as means of regulating internal temperature. In addition, inverters have critical temperature limits that, once reached, result in inverter shut down. Inverters also include one or more temperature switches as a backup safety mechanisms in the event of an uncontrolled temperature increase due to failures in the inverter's thermal management control systems. System designers should understand the inverter's maximum ambient operating temperature for full rated power and consider other factors that affect the inverter's operating temperature and cooling ability, including inverter shading, elevation, and mounting location (indoor/outdoor, ventilated/conditioned). Designers are encouraged to use good engineering judgment and attempt to promote optimal cooling of the inverter to ensure the longest life of the equipment. System owners should perform regularly scheduled maintenance of any air intake filters and cooling system.

Warranty

Discussions of inverter life and MTBF lead to perhaps the biggest question from designers, developers, and EPC's regarding oversizing: "How will oversizing effect my inverter warranty?" It is recommended to work closely with your inverter provider to understand how oversizing effects warranty and related offerings, such as preventative maintenance plans and uptime-guarantees.

What's Best and What's Next

If you have been reading this article seeking an answer to the question "what is the best oversizing ratio?" the answer should now be apparent that "it depends." Factors to consider include project location, design specifics, project cost structure, financial model, and other project goals.

How will oversizing practices change in the future? – a fair question considering the transition of design practices from "traditional" to "oversized" is proof of how design norms can change in a relatively short period. With the continued downward trend of module prices and the potential for an increasing number of utilities transitioning to time-of-use rate structures, combined with future technology to capture energy lost during power limiting or to temporarily overdrive inverters for grid support, indications are that the practice of oversizing only stands to continue.