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Response to Invitation to Participate - Solar Inverters

Additional submitted attachment is included below.

Solar Inverters

Codes and Standards Enhancement (CASE) Initiative
For PY 2017: Title 20 Standards Development

Response to the California Energy Commission's Invitation to Participate
Phase 2 Pre-Rulemaking
Solar Inverters
17-AAER-13

June 16, 2017

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1. Executive Summary

The Codes and Standards Enhancement (CASE) initiative presents recommendations to support the California Energy Commission's (Energy Commission) efforts to update California's Appliance Efficiency Regulations (Title 20) to include new requirements or to upgrade existing requirements for various technologies. The four California Investor Owned Utilities (IOUs) – Pacific Gas and Electric Company (PG&E), San Diego Gas and Electric (SDG&E), Southern California Edison (SCE), and SoCalGas® – sponsored this effort (herein referred to as the Statewide CASE Team). The program goal is to prepare and submit proposals that will result in cost-effective enhancements to improve the energy and water efficiency of various products sold in California. The information presented herein is a response to the Energy Commission's Invitation to Participate Phase 2 Pre-Rulemaking for the development of a "roadmap" for solar inverters.

The Statewide CASE Team supports the Energy Commission's decision to develop a roadmap to examine potential efficiency standards for solar inverters and power optimizers during both operational and non-operational modes. Solar panels are a very large source of power generation in California that continues to grow. In 2016, California's installed over 5,000 MW of solar power (customer sited and utility scale) with a cumulative capacity of over 18,200 MW (13.2 percent of state power production) (SEIA 2017). Solar energy use will continue to increase due to falling costs and aggressive California climate and renewable energy goals, such as Senate Bill 350, the Clean Energy and Pollution Reduction Act (de León), that was adopted in 2015. Addressing solar photovoltaic (PV) inverter efficiency has the potential to increase solar production. For example, for each additional 5,000 MW of solar capacity installed, just a tenth of a percent of inverter efficiency improvement achieved by standards and/or other policies would equal a 5 MW increase in installed capacity over the lifetime of the initial installations. In addition, the photovoltaic landscape is evolving through changes in industry structure as well as through technology innovation. The Statewide CASE Team recommends that the roadmap consider a range of current and emerging technologies including microinverters with integrated power optimizers, inverters without integrated power optimizers, and power optimizers.

The Statewide CASE Team has also provided background information regarding products and standards as requested by the Energy Commission. This document provides information about standards implementation for Arizona, Hawaii, and California public utilities as well as United States (U.S.) and international standards that contain procedures for measuring efficiency.

2. Product Definition and Scope

2.1 Solar Inverters

The Statewide CASE Team notes that inverters can be grouped into several major product categories that are explained here and used throughout this document. For instance, microinverters integrate power optimization with inverter features and mount directly on the module (typically in the 200-325 W range) either during manufacturing or field installation. In this situation a central inverter would not be needed; installers are able to use higher gauge (smaller diameter) wire from the roof.

Residential and smaller commercial string inventors (which service a string of PV modules) are another product grouping and are typically installed in a shaded area or indoors. For instance, over

1,000 units in the Energy Commission solar inverter database fall in the range of 2,000-7,000 watts.[1] Larger central inverter units serve large commercial and/or utility scale projects. These more traditional inverters can be combined with separate power optimizers as described in more detail below.

2.2 Power Optimization- Micro-Inverters vs. Central Inverters with Power Optimizers

The Energy Commission requested information on the following question: "Should the scope of this roadmap include power optimizers and other related electronics that interact with inverters?" The Statewide CASE Team recommends including power optimizers and other technologies, collectively referred to as Module-Level Power Electronics, or MLPEs. MLPEs include both microinverters with integrated power optimizers and standalone DC- DC (Direct Current) power optimizers.

An examination of power optimization requires a general understanding of the Maximum Power Point (MPP) and Maximum Power Point Tracking (MPPT). The MPP is the maximum power output in watts on the Current-Voltage (I-V) curve of a solar cell. The MPP Wattage is the product of the ideal current (Amp) and the Ideal Voltage (V) on the power curve. MPPT is the tracking of the maximum power point through a charge controller connected to a microprocessor, either integrated into a string/central inverter or micoinverter or as a standalone charge controller. Charge controllers integrated with a microprocessor are collectively refered to as power optimizers.

Power optimizers can be integrated into the module, installed at the module level or installed at the string level, in addition to being integrated into a string/central inverter or a microinverter. MPPT in a module level power optimizer continuously samples cell voltage and adjusts the current to optimize the power output from a single module in conjunction with other modules connected in a string. Power optimization at the string level optimizes the MPPT for a string in conjunction with other strings.

2.2.1 Power Optimization in Micro-Inverters

Power optimization inherently occurs in microinvverters. Microinverters have their differences from module-level power optimizers. Microinverters place the DC to Alternating Currnet (AC) conversion on the module, essentially creating AC solar PV modules. Optimizing MPPT can increase system conversion efficiency in most applications over solar PV systems with central string inverters and no module level power optimization.

Maximum Power Point Tracking (MPPT) and Power Optimization: Solar PV modules connected to centralized or string inverters have a disadvantage in that the weakest performing module in a string can reduce the efficiency of the entire string. In a prime solar installation where there is no shading from snow, leaves, dust, trees or other structures, and all of the panels are oriented in the same direction, this efficiency drag poses little problem. However, as the market progresses toward configurations with multiple orientations in a single array or in less optimal site types and climate zones, DC/DC optimization at the module level will improve overall project efficiency and economics. Microinverters typically optimize power production at the module level. Shifting priorities for when power production is most valuable may incentivize alternative array orientations, potentially increasing the importance of power optimization and MPPT.

[1] The Statewide CASE Team summed units listed in this range using data from the CEC 2017.

Compared to string inverters with module level power optimization, microinverters can be impacted by temperature to a greater extent than string inverters. Inversion creates heat, thus the loss in efficiency of an inverter due to heat losses, which in turn lowers the cell efficiency of the panel. The net efficiency loss due to heat gain depends on how the micro-inverters are attached to the module laminate. Additionally, the inverters are then exposed to the elements, potentially decreasing their longevity compared to a solid state power optimizer attached to the panel with power inversion occurring at the central inverter.

2.2.2 Power Optimization in Central Inverters

Central inverters can come pre-installed with power optimization that allows for MPPT at the string level in a system configuration with multiple module strings connected to a single central inverter. Solar PV systems can also be connected with standalone power optimizers at the module level to allow for MPPT and real time system monitoring at the module level. Due to the ability of module level power optimizers to account for shading, standalone power optimizers are typically mounted on modules and rely on separate string or central inverters to convert DC power to AC power. A number of large module manufacturers integrate power optimization directly into the module itself at the factory to reduce installation and wiring costs. These modules are often referred to as "Smart Modules" or "AC Modules."

2.2.3 Benefits of Power Optimizers in PV Systems

Excluding power optimizers and other MLPE technologies from this roadmap that compete with microinverters would exclude a significant segment of the market and could lead to bias in the results of any evaluation of product efficiency and/or functionality. Furthermore, traditional string inverters may provide different functionality compared to microinverters.

Power optimizers create value in solar PV asset management and power delivery by allowing for module-level monitoring and troubleshooting, and MPPT at the module or string level as described further in Appendix A. Unlike microinverters, which perform optimization and DC to AC power conversion at the module, power optimizers perform DC to DC optimization and monitoring while central or inverters perform the DC to AC conversion. Power optimizers can also facilitate important safety functions required under NEC 2014 article 690.12, which has been adopted in California and most other states as well.[1]

Thus, the most relevant question may be: Should the scope of the roadmap include MLPEs integrated directly into modules, or as separate units, thus examining current technology and future technology commercialization trajectories? Inclusion of MLPEs will become even more important as this equipment continues to gain increasing market share as shown below in Figure 1.

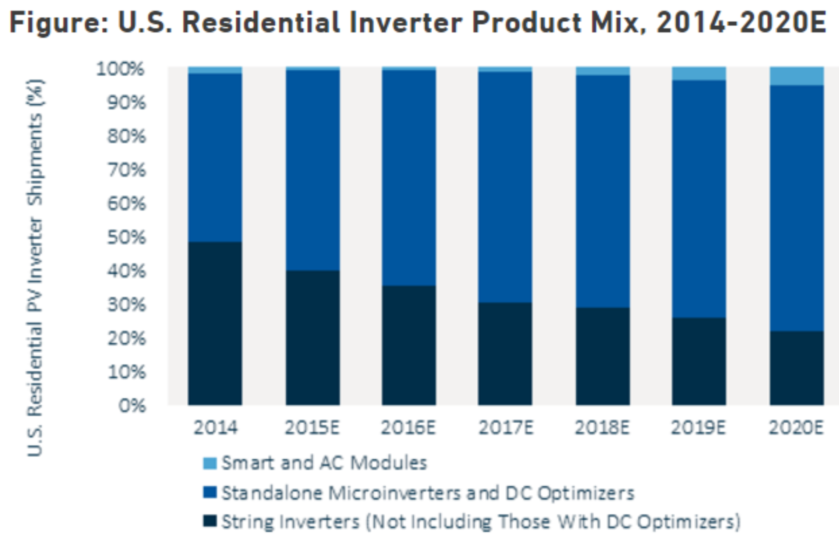

Figure 1: U.S. Residential Inverter Product Mix

Source: https://www.greentechmedia.com/articles/read/will-the-us-mandate-module-level-power-electronics-in-2017

As the industy moves towards prioritizing monitoring, module level control, and safety, solar panels will likely become “smarter” and may begin performing some of the tasks often handled by smart inverters and in operations and maintenance (O&M) contracts.[2] A roadmap inclusive of MLPEs should consider the benefits of enhanced functionality to improve safety, power production and grid services and potentially additional operational and/or maintenance benefits in combination with unit and system level energy efficiency.

3. Test Procedures

The Energy Commission requested information on the following question: “What test procedures are available specific to conversion efficiency and MPPT efficiency?”

3.1 What test procedures are available specific to conversion efficiency and MPPT efficiency?

A number of U.S. and international standards measure inverter conversion and MPPT efficiency (see Appendix A for more information regarding MPPT efficiency). The most widely accepted testing standards are the following:

- European Committee for Standardization (CEN) EN 50530 Standard – Overall Efficiency of Grid Connected Photovoltaic Inverters
- International Electrical Commission (IEC) 61683 Standard – Power Conditioners – Procedure for Measuring Efficiency
- Energy Commission Guidelines – Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems

[2] For instance, US Patent number US9496710B2 was granted to Solar City for solid state circuitry integrated into PV modules that allows for “rapid shutdown” of individual modules in response to NEC 2014 article 690.12.

Each of these standards are robust and similar in application, the exception being that the CEN EN 50530 Standard and the Energy Commission Guidelines are more focused on grid-tied solar PV systems while the IEC 61683 standard includes both stand-alone and grid-tied solar PV systems. The major differences can be summarized as follows:

EN 50530 – This standard contains procedures to determine MPPT efficiency in grid tied situations specific to the European solar market. The standard requires the use of a set of weighted factors associated with the static MPPT efficiency and the DC to AC conversion efficiency to determine total inverter efficiency. However, "[T]he dynamic behaviour of the MPPT algorithm - e.g. on cloudy days with frequent and rapid changes of irradiance - is not reflected in the static figures. In locations where such conditions predominate, this dynamic behaviour is also an important issue." (Jantsch, undated) In addition to using the static MPPT efficiency, the EN 50530 standard also contains procedures to determine and report the dynamic MPPT efficiency (European Center for Standardization (CEN) 2010)).

IEC 61683 – This standard contains procedures to determine the overall efficiency of inverters in both grid-connected and off-grid applications through direct measurement of input and output power. The standard uses dynamic MPPT adjustments to the input power to factor the contribution of MPPT efficiency into the total inverter efficiency (International Electrochemical Commission 1999). The Statewide CASE Team is working to better understand how the MPPT is reported under the international standard and to better understand how the IEC 61683 standard compares to both the EN50530 Standard and the Energy Commission Guidelines.

California Energy Commission Guidelines – This standard is similar to the EN 50530, but uses different factors to weight MPPT efficiency under different operating conditions in calculating the standard to better represent California's market conditions and climate (European Center for Standardization (CEN) 2010).

The Statewide CASE Team continues to evaluate the various California and international inverter efficiency standards and guidelines to compare and contrast the calculation methodologies and the way that these standards determine MPPT efficiency.

4. Market Characteristics

The Energy Commission requested information on a number of topics regarding market characteristics.

4.1 What are the estimated number of inverter sales by product category in California?

The "NEMs Currently Interconnected Data Set" available from www.calfironiadgstats.ca.gov currently provides extensive information regarding inverter sales by product category in IOU service territories, such as microinverters and smaller and larger size string inverters. The Statewide CASE Team is also currently evaluating the availability of other data sources covering other utility areas in California.

4.2 Are publicly owned utilities also planning to require inverters that have been evaluated per UL 1741 SA or are there inconsistent interconnection requirements in CA?

Of the publicly owned utilities, the Los Angeles Department of Water and Power (LADWP) and the Sacramento Municipal Utility District (SMUD) have the largest market share with over two million electric power customers across their respective territories (Sacramento Municipal Utility District (SMUD) 2017, and Los Angeles Department of Water and Power (LADWP) 2017). The remaining 26 publicly owned utilities are organized into the Northern California Power Agency (NCPA) and the Southern California Public Power Authority (SCPPA), the latter of which also includes LADWP. While the Statewide CASE Team has not catalogued all of the public utility interconnection requirements across the state, a brief examination of SMUD and LADWP indicate that California public utilities do not consistently require full compliance with UL 1741 SA, or at least have a different process to do so. In the case of SMUD, all distributed generation resources connecting to the utility's distribution system are required to comply with the mandatory requirements outlined in Rule 21. SMUD's policy and procedure document 11-01 outlining interconnection guidelines specifically requires in section 14.2 that the use of equipment certified by both UL 1741 SA and IEEE 1547 are required for interconnection to their system (Sacramento Municipal Utility District (SMUD) 2015).

LADWP may require some of the same standards, but follows a different process in defining interconnection standards for inverters. Unlike SMUDs explicit interconnection requirements, LADWP's interconnection requirements are integrated into the permitting process for the facility and solar incentive program in which they intend to participate (Los Angeles Department of Water and Power 2017). In the Statewide CASE Team's initial review, the interconnection requirements do not explicitly state that they must meet Rule 21 or UL 1741 SA requirements to interconnect. Rather, the system must meet the zoning, permitting, and fire safety requirements outlined in the City of Los Angeles's distributed solar resource guide.[3]

The LADWP interconnection permitting requirements are spread across various Los Angeles Department of Buildings & Safety (LADBS) permitting guidelines. These guidelines vary based on the type of permit required and the planning conditions that must be met. For LADWP customers installing systems smaller than 10 kW-AC, an interconnection agreement is not required, and these systems may qualify for an express permitting process if a standard set of conditions is met. While the permitting guidelines may have some overlap with Rule 21 and UL 1741 SA, especially around fire safety, the Statewide CASE Team did not find any general requirement to meet the UL 1741 SA or Rule 21 requirements.

4.3 What additional inverter functions are being mandated in Hawaii and other states?

While the Statewide CASE Team has not reviewed every state's requirements, the team has determined that Hawaii and Arizona are helpful examples to review, because they have mandated or are evaluating inverter functions that could be mandated. In addition, both states participated in the Solar Inverter Working Group (SIWG) to establish the test procedures for autonomous functionality

[3]See http://www.gosolarcalifornia.ca.gov/resources/socal_jurisdictions/cities/City_of_Los_Angeles.pdf

that are the foundation of UL 1741 SA, much of which is or may be required of California Investor Owned Utilities and others under Rule 21 (Laboratory 2017).

The state of Hawaii is a leader in the development of smart inverter functionality mandates in the U.S.. Hawaii has greater than 15 percent penetration of distributed energy resources (DERs) on many parts of its grid, greatly increasing the need for standards related to smart inverter functionality for grid tied inverters and providing a good model for states with high levels of DERs (Trabish 2016). Standards implementation is easier than in some states. For example, Hawaii has a single IOU, the Hawaii Electric Company (HECO), serving 95 percent of the state load with the remaining 5 percent provided by the Kauai Island Utility Cooperative (KIUC) (Hawaiian Electric Industries 2017). Hawaii has fully adopted both the seven required standards and the two optional standards under UL 1741 SA, shown in Table 1, as well as two additional inverter standards for system disconnect/reconnect and remote configurability not covered in UL1741 SA (Fong 2015 and Underwriters Laboratory (UL) LLC 2016).

Table 1: Comparison of the Hawaii Smart Inverter Requirements and UL 1741 SA Inverter Standards

Hawaii Smart Inverter Requirements	UL 1741 SA Test Standards
Anti-Islanding	Anti-Islanding
Low/High Voltage Ride-Through	Low/High Voltage Ride-Through
Low/High Frequency Ride-Through	Low/High Frequency Ride-Through
Volt-VAR Control	Volt-VAR Control
Ramp Rate	Ramp Rate
Fixed Power Factor	Fixed Power Factor
Soft-Start Reconnection	Must Trip Test
Frequency Watt	Frequency Watt (Optional)
Voltage Watt	Volt Watt (Optional)
Remote Reconnect/Disconnect	NA
Remote Configurability	NA

Arizona offers an example of a somewhat more decentralized approach. Arizona's two major public and investor owned utilities, Salt River Project (SRP) and Arizona Public Service (APS), are launching pilot programs to study and understand smart inverter functionality, efficiency, and grid benefits in response to a large amount of solar penetration on their distribution and transmission network. Collectively, these two utilities make up about 85 percent of the Arizona's retail residential, commercial, and industrial electricity sales.

APS has created an inverter study pilot as part of its Arizona Corporation Commission (ACC) approved Solar Partner Program. The program will test a utility ownership model for solar resources deployed in Phoenix to delay transmission and distribution grid upgrades (John 2015). The program aims to install up to 1,500 solar systems and inverters on primarily westerly facing singlefamily rooftops and a smaller number of systems on southwest and south-facing study control groups to determine the efficacy of smart inverters in meeting grid stability requirements (John 2015). The program will use APS' automated control system in conjunction with these utility owned smart inverters to evaluate the ability of fully autonomous functions and smart inverters to accomplish the following:

- Use the inverter to respond during contingency events;

- Improve overall power quality;
- Develop a better understanding of Solar output and system demand; and
- Evaluate capabilities of grid-tied battery storage at the distribution feeder level.

SRP has designed and implemented a similar program called the Advanced Inverter Project. This project links 1,000 smart inverters to existing PV systems to study their benefits to the grid and unlock more value from solar. SRP will be testing capabilities of a number of inverters through autonomous control schemes (John 2015).

The Statewide CASE Team is continuing to evaluate the level of public data available from these programs to date and expects them to provide significant real-world information on inverter functionality, MPPT efficiency, and overall inverter efficiency in alternative configurations.

4.4 How many small businesses are involved in the manufacturing, sale, or installation of these products?

The Statewide CASE Team notes that manufacturing of solar inverters and power optimizers is typically conducted by large international firms. Sales and installation can be conducted by large or small firms. The Statewide CASE Team is currently researching the potential role of small businesses in this market.

5. Product Lifetime

The Energy Commission requested information on the following question: What is a reasonable estimate of inverter lifetime and does it vary based on product category?

Microinverters typically carry a warranty of 20-25 years. String and central inverters commonly carry a warrantee of 10-12 years. The actual lifetime may vary based on conditions. The Statewide CASE Team notes that warrantees are often set so that products will survive the warrantee period even during unfavorable conditions, resulting in an average product lifetime exceeding the minimum warrantee period. The Statewide CASE Team is currently investigating the availability of any studies that document expected average lifetime of solar inverters and associated products.

6. Potential Efficiency Regulations

6.1 What would be the benefits of mandatory testing and reporting requirements?

In general, mandatory testing and reporting are appropriate where needed to fill in data gaps and help determine whether Title 20 Standards and/or other policies are justified. For instance, if currently available testing and reporting does not fully capture the performance of current and emerging technologies under a representative range of field conditions, additional testing and reporting may be warranted. As noted earlier, the Statewide CASE Team is continuing to evaluate existing test methods. In addition, the Statewide CASE Team recommends that the Energy Commission address whether the phase-out of the California Solar Initiative incentive program may reduce reporting for solar inverters and related products in the future. If any gaps are likely to occur prior to the Energy Commission's consideration of Title 20 Standards, mandatory testing and reporting could fill the gaps.

The Energy Commission also noted that "very high levels of conversion efficiency are already demanded by purchasers of solar inverters." The Statewide CASE Team agrees that market forces have provided a valuable driver for efficiency, and believes that the Energy Commission roadmap for solar inverters and associated products can play a valuable role by determining whether standards and/or other policies are needed to overcome market barriers for efficiency opportunities, especially as subsidies are phased-out. Below, the Statewide CASE Team discusses two specific examples raised by the Energy Commission for MPPT and stand-by losses. The Statewide CASE Team also recommends that the Energy Commission address how the voltage range for a solar inverter could limit or enhance a solar system's ability to produce power at low solar irradiance (which may result in reduced voltage), and whether that value is currently reflected in the weighted efficiency value reported to the Energy Commission.

6.2 What would be the benefits of requirements regarding MPPT efficiency?

6.2.1 MPPT test methods

Ideally the Energy Commission would study MPPT algorithms and evaluate whether any gaps in current MLPE testing methods exist when evaluating existing and emerging technologies in different solar PV applications types, use cases, and climate zones. Different module and inverter pairings, system configurations, and system use cases will impact MPPT efficiency as these factors can impact dynamic system output voltage. The maximum power point is the point on the Current-Voltage (I-V) curve equivalent to the peak voltage of the system power curve and the corresponding current on the I-V curve (Musser 2009). MPPT mandatory testing and reporting standards must consider these factors in the development of the test procedures.

6.2.2 Efficiency standards

The Statewide CASE Team supports including evaluation of potential standards within the scope of the roadmap. Standards may be justified where market barrier prevent market adoption of energy efficient technology. For instance, consumers may lack the expertise to evaluate highly complex efficiency calculations. In addition, current metrics may not capture factors, such as solar inverters voltage range, which could influence efficiency. In battery integrated systems, the voltage range directly impacts the ability to charge the system, making power optimizers a necessary system component to maximize charging efficiency. Power optimizers use charge controllers and microprocessors to match the system output voltage to the battery system voltage requirements based on the battery state of charge.

In grid connected systems, the grid impedence against the AC current created by the inverter results in a voltage rise at the inverter AC bus, causing a voltage rise relevant to the grid Point of Common Coupling (POCC). The voltage rise of the inverter relative to the POCC is the same as a voltage drop at the POCC, and the percentage voltage drop at this point is proportional to the percent of power and energy lost at the interconnection point, resulting in lost revenue and reduced system efficiency at the interconnection point (White, 2012). In addition to the voltage rise, inverter range impacts the nuisance tripping tolerances of the inverter as outlined in UL 1741 and IEEE 1547.

Given the large scale of solar power in the state, even small efficiency increases can add up to substantial benefits. For instance, for the next 5,000 MW of solar installed in CA, each 0.1 percent efficiency improvement achieved will increase capacity of systems installed in a given year by 5 MW over the 10-25-year lifetime.

6.3 What would be the benefits of limiting self-consumption during non-production hours, similar to a standby power requirement?

The Statewide CASE Team recommends that the Energy Commission consider a limit on self-consumption power use during non-operational modes for several reasons:

- These losses will not be captured by typical metrics used to evaluate solar inverter efficiency during solar power production.
- Given that these loses will occur during non-solar hours, they may disproportionately affect future system reliability if overall electricity grid generation is maximized during the solar peak.
- Doubling current solar production of over 18,200 MW (13.2 percent of state production) would lead to 18.2 MW increased production for each tenth of a percent increase in efficiency. Depending on the reasons for the losses, improvement in stand-by efficiency could also spill over into operational efficiency as well. Thus, even relatively small changes in efficiency at the unit level can result in substantial overall benefits.

The U.S. Environmental Protection Agency (EPA) ENERGY STAR® Specification for Electric Vehicle Supply Equipment during stand-by mode is one potential model for how to structure a potential standard for solar inverter stand-by losses. Each unit receives a base allowance, which is supplemented by adders for communications features and certain other features. In particular, the Statewide CASE Team also suggests that the Energy Commission consider an adder for features necessary to provide functions that are or will be required by Rule 21, for instance, during any consideration of a Title 20 Standard.

7. Other Considerations

There are many activites in California relating to distributed solar which impact inverters. The Statewide CASE Team encourages the Energy Commission to stay abreast of these efforts throughout this roadmapping effort.

Updating NEM 2.0 and Virtual Net Metering[4]

Over the last few yars, the IOUs have been working to update their net energy metering (NEM) tariffs to better account for sustainable solar growth in CA. There are many moving pieces with NEM reform and we encourage CEC to monitor these efforts through this rulemaking

Smart Inverter Working Group & Rule 21[5]

The Smart Inverter Working Group (SIWG) grew out of a collaboration between the CPUC and California Energy Commission (CEC) in early 2013 that identified the development of advanced inverter functionality as an important strategy to mitigate the impact of high penetration of distributed energy resources (DERs), such as solar PV. The IOUs have participated in this working group which has pursued the development of advanced inverter functionality over three phases. Phase 1 considered autonomous functions that all inverter-connected DERs in California will be required to perform, and will go into effect for all new interconnections in IOU territories in September, 2017. Phase 2 considered the default protocols for communications between IOUs, DERs, and DER aggregators. Phase 3 is currently considering additional advanced inverter functionality that may or may not require communications. These recommendations have or will be required via the CPUC Rule 21.

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[4] See here for more information: http://www.cpuc.ca.gov/General.aspx?id=3800

[5] See here for more information: http://www.cpuc.ca.gov/General.aspx?id=4154 and http://www.cpuc.ca.gov/Rule21/.

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Appendix A: MPPT Efficiency

This Appendix provides a description of MPPT efficiency.

MPPT algorithms are based on specific load curves that are designed around parameters for irradiance and temperature, for a specific PV solar module as shown in Figure 2. These algorithms are coupled with a power optimizer. The voltage providing maximum power output will vary over time for a given module based on temperature and solar irradiance, requiring a dynamic response due to changing environmental conditions and any shading that occurs.

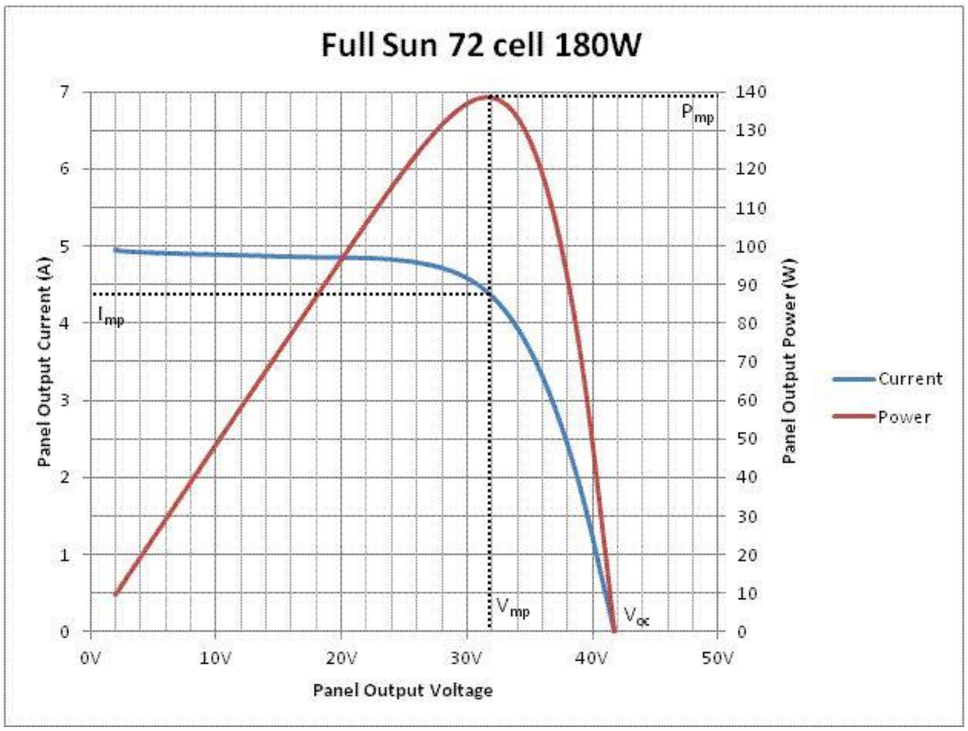

Figure 2. PV Solar Power Curve Example

Source: Linear.com

Microinverters

With microinverters, MPPT occurs at the individual module level via a power optimizer integrated with the microinverter. This method allows greater individualization of module output if for instance an individual module is differently affected by shading or deterioration due to aging. These conditions may be especially valuable in rooftop applications in developed areas where the potential for shading may be higher than in remote locations.

Microinverter MPPT also potentially allows greater flexibility to match panels that are not identical, such as a replacement module or expansion that may not exactly match the original panels, without sacrificing individual maximum efficiency operating points.

Power optimizers that are installed at the module level may offer the same opportunity to maximize individual module production (without also providing inverter functions).

Central/string inverters

Central and string inverters typically control MPPT at the string level, allowing for the optimization of the Maximum Power Point (MPP) of each individual string. As an example, in a configuration where shading from panels, a tree, structure, or cloud cover occurs during the day, an inverter with single MPPT can be used to maximize inverter efficiency across a string of PV solar modules with similar azimuthal and tilt angles in a north-south orientation. In these cases, mismatches can occur and shift during the day across the various parts of the array due to the dynamic direct irradiance across the system. However, adjustment at the string level may not optimize the performance of individual panels that are differently affected by shading and/or aging, and a single sub-optimal module can limit production of an entire string.

Dual or Multi MPPT central/string inverters can allow for improved flexibility and efficiency. Multi-point MPPT allows for the assymetrical configuration of individual strings for each MPPT channel on the inverter, so that strings with different orientations or shading (for instance, on different sides of a sloped roof) can be separately controlled to optimize production. This approach may greatly reduce both the inverter and balance of system costs for the solar PV system compared to installing separate inverters for each string (Zipp 2017).[6]

[6] Inverters that perform MPPT in solar PV-storage hybrid configurations also allow for MPPT during the dawn hours when the batteries are partially discharged and drawing power at a lower voltage than that at the MPP of the solar array.