ENERGY STAR Market and Industry Scoping Report
Solar Inverters
December 2013

The U.S. Environmental Protection Agency (EPA) consistently looks for new opportunities to expand ENERGY STAR to new product categories that will deliver significant benefits to consumers and the environment in the form of energy and dollar savings plus greenhouse gas reductions. A key step in this evaluation is the development of a scoping report that provides a snapshot of the product market, energy use, and savings potential associated with an ENERGY STAR program for the scoped product type. EPA uses scoping findings to prioritize product specification development work. While scoping reports are drafted primarily for internal evaluation purposes, and are not intended to be exhaustive but rather a guidepost for the ENERGY STAR program, EPA makes the reports available with the interest of benefiting other efficiency programs evaluating similar opportunities. For more information about the ENERGY STAR specification development process, go to: www.energystar.gov/productdevelopment.

1. Executive Summary

- The U.S. market for solar photovoltaic (PV) power is booming with significant growth in the residential sector.
- Transformerless inverters are the most efficient technology, while micro-inverters, provide a novel opportunity to extract more power from individual PV panels.
- Smart inverter technology will enable PV and other distributed generation and storage to enhance rather than degrade grid stability. This technology is needed today in regions with high solar PV penetration, such as Oahu. However, standardization of U.S. smart inverter functionality and communications is currently a work-in-progress with a number of recommended functions in conflict with the UL 1741 safety standard. As such, smart inverters are not currently available in the U.S.

2. Definitions

The following definitions, except where noted, have been taken verbatim from the Solar-is-Future website.[1]

Grid-connected system: A grid-connected photovoltaic system is one which feeds the electricity it generates into the electricity grid.

Stand-alone system: Stand-alone systems facilitate a self-sufficient energy supply and are primarily used in areas that are not connected to the electricity grid. In order to ensure a continuous energy supply, any surplus solar power that is generated is stored in batteries and is taken from these at night (or in case of need).

Solar cell: In solar cells, which in most cases are made of silicon, the influx of light or heat causes positive and negative charge carriers to be emitted (photoelectric effect), thereby producing a direct current. Different material compositions yield different efficiencies:

- Monocrystalline silicon: 14–17%

[1] SMA Solar Technology. “Glossary”, *Solar-is-Future.com,* http://www.solar-is-future.com/faq-glossary/glossary/index.html.

- Polycrystalline silicon: 13–15%
- Amorphous silicon: 5–7%

Thin-film cell: Photoactive semiconductors are applied on a substrate (glass, stainless steel foil) to form a thin film. The advantages of thin-film cells are their low manufacturing costs, lower susceptibility to shading and greater shape flexibility. One drawback is the lower efficiency compared with pure crystalline silicon cells.

Photovoltaic module: A photovoltaic or Solar module consists of several interconnected solar cells that are embedded between two glass or plastic plates and are therefore protected from the effects of the weather. As a rule, the modules are installed in a frame on a rooftop or a support mount.

Charge controller: Used in stand-alone and hybrid solar PV systems, the charge controller connects the battery storage to the solar PV array and provides voltage and/or current regulation to prevent over-charging. Charge controllers come in 3 general types with maximum power point tracking (see definition, below) only on the most expensive and efficient models.[2]

Inverter: The direct current generated by the solar cells is converted to grid-compatible alternating current by the inverter. It is therefore the link between the solar modules and the electricity grid.

> **Central inverter:** Central inverters are particularly suitable for building up photovoltaic systems with a homogeneous structure (modules of the same type with an identical alignment and inclination). They are used for installations from 100 kW upwards and, in most cases, are designed for outdoor installation.
>
> **String inverter:** In string technology, the photovoltaic generator is subdivided into individual module surfaces and each of these individual "strings" has its own string inverter allocated to it. This technology allows the system costs to be reduced while at the same time making installation a lot easier and increasing the energy yield and system availability.
>
> **Multi-String inverter:** An inverter which, to a large extent, combines the advantages of several string inverters (separate MPP control of individual strings) and a central inverter (low output-related costs).
>
> **Micro-inverter:** A micro-inverter is a device that takes the DC output of a single solar module and converts it into grid-compliant AC power.[3]

Smart Inverter: These inverters are capable of receiving and responding to grid signals in order to help keep the power grid stable, by for example, disconnecting from the grid in a controlled manner to prevent a sudden change in load when numerous inverters disconnect at once.[4]

Maximum Power Point (MPP): The electrical power of a solar cell under a given amount of solar radiation depends on the voltage and cell temperature. MPP (Maximum Power Point) stands for the operating point at which this power reaches a maximum. The MPP changes

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[2] Northern Arizona Wind & Sun, “Everything you Need to Know About the Basics of Solar Charge Controllers”, http://www.solar-electric.com/solar-charge-controller-basics.html.

[3] Enphase Energy, “Enphase Micro-inverter System”, presentation, http://www.slideshare.net/ccsemedia/9096-enphase-introduction.

[4] Solar Oregon, “What Is a Smart Inverter Anyway?”, http://solaroregon.org/news/what-is-a-smart-inverter-anyway.

constantly (depending on the solar radiation and the temperature) and has to be detected anew continuously (Also see MPP Tracker).

MPP Tracker (MPPT): A device which adjusts the current and voltage of the photovoltaic generator to ensure that it operates at "Maximum Power Point".

Module Level Power Management (MLPM): Inclusive term that describes system topologies that provide MPP tracking on a per PV panel basis versus on the PV array as a whole. MPLM includes both micro-inverters and solar power optimizers.

Efficiency (PV System): Efficiency refers to the ratio between energy outputs and inputs. By way of illustration: conventional light bulbs convert approximately 3–4% of the energy input into light, while photovoltaic systems / solar cells currently achieve an efficiency of 11–17%.

Energy Payback Time: The period of time that a solar power system requires to generate as much energy as was required for its manufacturing. The energy return times of photovoltaic systems are between three and maximum seven years. According to a study performed by the Technical University of Berlin, PV plants that are based on amorphous silicon have an energy payback time period of only 17 to 41 months. Thus, PV plants have a positive energy balance. Power stations that are operated with fossil fuels cannot achieve energy payback, since they constantly consume additional fuels.

3. Residential Solar PV Systems – Key Types

Stand-Alone (off-grid) Solar PV System: Typically only used in remote installations where grid interconnection is not available.

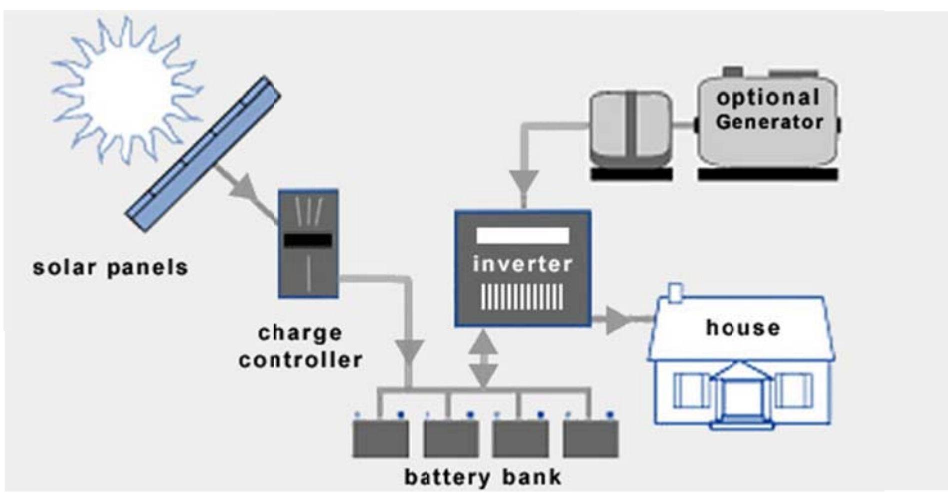

Figure 1: Stand-Alone Solar PV System[5]

Grid-Connected Solar PV System: These systems generate AC line voltage, synchronized with and connected to electric utility power. In most jurisdictions, net-metering is allowed or mandated, enabling excess production to “spin the meter backwards” and be sold back to the

[5] M. A. Maehlum, “Grid-Tied, Off-Grid and Hybrid Solar Systems”, *Energy Informative*. 14 August 2013, http://energyinformative.org/grid-tied-off-grid-and-hybrid-solar-systems/.

electric utility. However, since these systems must automatically disconnect from the grid during outages, they are not capable of supplying energy to the home during outages.

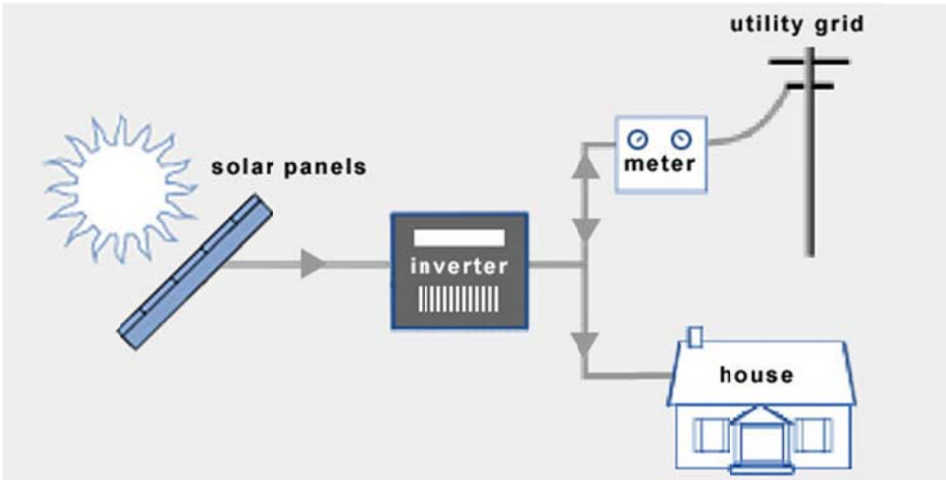

Figure 2: Grid-Connected Solar PV System[6]

Hybrid Solar PV Systems combine elements of both grid-connected and standalone systems. They are grid-connected and enable excess energy to be sold. Hybrid system architectures include energy storage as well as the ability to disconnect from the grid, but still supply energy to the home during outages.

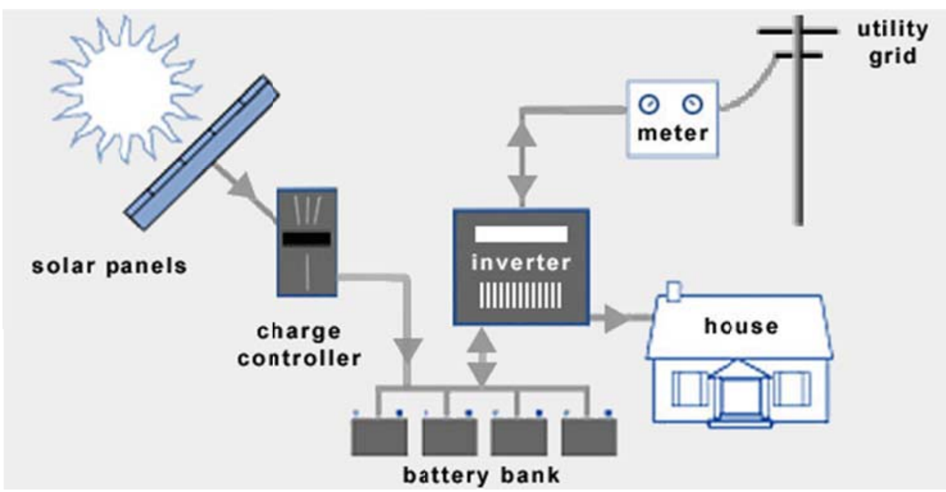

Figure 3: Hybrid Solar System[7]

[6] Ibid.

[7] Ibid.

4. Product and Technology Overview

Solar Photovoltaic (PV) Inverters designed for the North American market convert Direct Current (DC) voltage generated by photovoltaic panels into standard 60 Hz / 120V Alternating Current (AC) line voltage. PV inverters fall into two broad categories, standalone and grid-interactive, also known as grid-tied or grid-connected. According to Greentech media, advances in PV inverter technology continues to deliver more sophisticated grid support and PV system optimization.[8]

As standalone inverters are generally limited to a small market, for use in remote locations where grid interconnection is impractical or unavailable, this study focuses on the broader market for grid-interactive PV inverters. Table 1 details the different types of grid-interactive PV inverters.

Table 1: Grid-Interactive PV Inverter Product Types

Product Type	Description	Details
Central / String Inverter – Low-Frequency Transformer	The legacy standard – in most residential PV installations, a single remotely located central/string inverter is required	Low-Frequency Transformer PV inverters convert DC voltage directly to 60 Hz / 120V AC line voltage
Central / String Inverter – High-Frequency Transformer	Functionally equivalent to low-frequency transformer PV inverters	High-Frequency Transformer PV inverters are reportedly more energy efficient than their low-frequency counterparts. They convert DC voltage in a multi-step process, first to high-frequency AC, back to DC and then to 60 Hz / 120V AC line voltage.
Central / String Inverter – Transformerless	Lighter, more compact and functionally equivalent to low and high frequency transformer inverters	Transformerless inverters use electronic components to first convert to high-frequency AC, back to DC, then to 60 Hz / 120V AC line voltage. No electrical isolation between DC and AC circuits is provided. Therefore, more expensive PV cables are required. Advantages: lower weight, higher efficiency, may have dual MPPT inputs, which enables independent MPPT on two PV arrays in order to maximize energy production.
Micro-inverter	In contrast to central/string inverters, a micro-inverter is connected to each individual PV panel, typically attached to the mounting framework or to the back of the panel.	Micro-inverters represent a technology shift for which manufacturers claim an increase in energy production of 5–25% relative to central inverter systems. In contrast to a traditional system where an underperforming panel can bring down the performance of the entire array; with micro-inverters, MPPT is employed to maximize power transfer on a per-panel basis. In addition to MPPT functionality, micro-inverters also convert DC voltage from to 60

[8] M.J. Shiao, "The Global PV Inverter Landscape 2013: Technologies, Markets, and Survivors", *GTM Research,* 18 April 2013, http://www.greentechmedia.com/research/report/the-global-pv-inverter-landscape-2013.

		Hz / 120V AC line voltage. Disadvantage is higher cost.

Solar power optimizers – These are *not* inverters, but when used with central inverters, can increase system power generation. Tigo Energy and SolarEdge manufacture power optimizers. Similar to micro-inverters, these devices are connected to and optimize power output from each individual PV panel. However, these optimizers are DC to DC converters that are used with a central transformerless string inverter. Both Tigo Energy and SolarEdge optimizers include communications that enable panel level monitoring and fault detection. Tigo claims their technology generates 2–4% more energy and is more cost effective than micro-inverters for all size systems.

5. Market Assessment

2013 will be a banner year for new solar PV installations. According to the Solar Energy Industries Association,[9] 930 megawatts (MW) of solar PV generation was installed in Q3 of 2013 alone, up 20% from Q2. Q3 installations represent the second largest number in the U.S. and the largest for residential PV, representing 52% growth in the residential sector. Total U.S. PV capacity now exceeds 10 GW. Other key findings:

- Over half of the new PV capacity was utility solar
- New Q3 residential PV capacity was 186 MW
- Average PV system prices fell 4.2% in Q3 relative to the prior quarter
- A total of 4.3 GW of new PV capacity is forecasted for 2013, up 27% from 2012.
- Average residential system size is 6 kW
- Residential system cost per kW has dropped 9.7% from $5.22/W in Q3 2012 to $4.72/W in Q3 2013. Q3 2013 cost per kW for non-residential and utility systems also dropped to $3.96/W and $2.10/W, respectively.
- The US is projected to install more solar capacity than world leader Germany in 2013.

Figure 4 illustrates global PV inverter shipments for 2011 through 2016 (estimated shipments from 2013-2016). Note that micro-inverter shipments are currently a very small fraction of the total but are projected grow rapidly after gaining initial traction in the US. According to IMS Research, worldwide shipments of micro-inverters and power optimizers, collectively known as

[9] Solar Energy Industries Association, "Solar Market Insight 2013 Q3", http://www.seia.org/research-resources/solar-market-insight-2013-q3.

Module Level Power Management (MLPM) solutions will increase from approximately 500 MW in 2013 to 2.1 GW in 2017.[10]

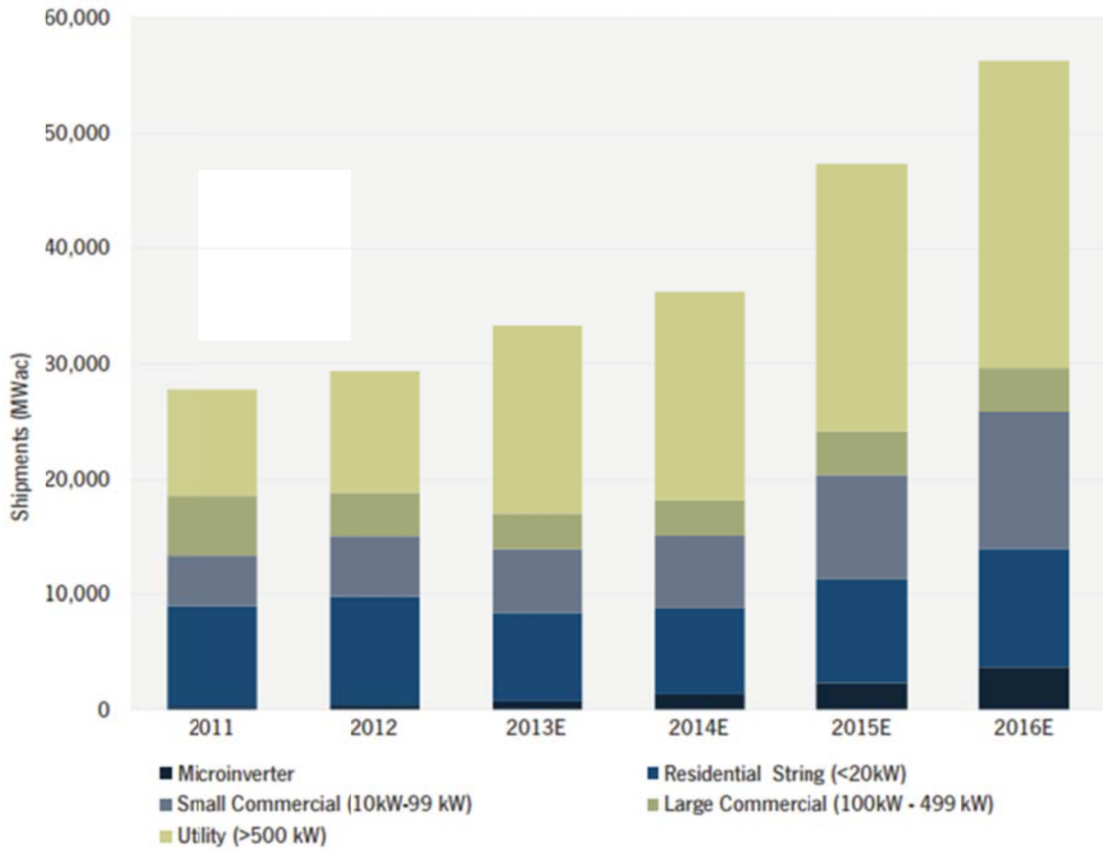

Figure 4: Global PV Inverter Shipments, 2011–2016[11]

In its Q1 2013 world market for PV Inverters report, IMS Research reported that the top 10 PV inverter companies lost market share from 62% in 2012 to 56% in 2013.[12] Lack of market presence coupled with strong price pressure and growth in demand in China and Japan has contributed to this decline. Amongst market fragmentation, the global leader, SMA has seen its share of global PV inverter revenue shrink from 40% in 2009 to 25% in 2012. Table 2 lists the top ten PV inverter manufacturers, including change in rank.

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[10] IMS Research, "The World Market for PV micro-inverters and Power Optimizers", http://www.pvmarketresearch.com/latest-news/press-template.php?pr_id=3683.

[11] Shiao.

[12] S. Ali-Oettinger, "Fall in Market Share for Top Ten PV Inverter Suppliers", *PV Magazine*, 2 May 2013, http://www.pv-magazine.com/news/details/beitrag/fall-in-market-share-for-top-ten-pv-inverter-suppliers_100011132/#axzz2oKAM9lt0.

Table 2: IMS Q1 2013 Top Ten PV Inverter Manufacturers

2012 IMS Rank	Manufacturer/Country	Change from 2011 Rank
1	SMA / Germany	-
2	Power One / USA	-
3	Kaco / Germany	-
4	Advanced Energy / USA	+4
5	Fronius / Austria	-1
6	Enphase Energy* / USA	+5
7	Danfoss Solar Inverters / Denmark	+5
8	Omron Corporation / Japan	+6
9	RefuSol / Germany	-
10	Schneider Electric / France	-3

6. *Test Standards & Metrics*

California Energy Commission

The California Energy Commission (CEC) maintains a list of eligible grid-interactive PV inverters.[13] Inverters are added to the list when manufacturers provide inverter test data in accordance with Appendix B, Section B of the Guidelines for California's Solar Electric Incentive Programs (Senate Bill 1), Fifth Edition. Inverters must be tested by a Nationally Recognized Testing Laboratory (NRTL) to the following criteria in order to be added:

1. UL 1741 listing;
2. Conversion efficiency data on a minimum of 5 test samples (efficiency data is used in rebate calculations) ; and
3. PV inverters, among other system components, must have a warranty of at-least 10-years.

CEC maintains a List of Eligible Inverters that also includes links to:

- The PV Inverter Performance Test Protocol;
- The Guidelines for use of the Performance Test Protocol; and
- Performance test data of all eligible grid-interactive PV inverters.

European vs CEC Efficiency

"European Efficiency" is a weighted average operating efficiency over a yearly power distribution corresponding to a middle-European climate. Proposed by the Joint Research Center (JRC/Ispra), based on the Ispra climate (Italy), European Efficiency is now referenced on almost all inverter datasheets. The value of this weighted efficiency is obtained by assigning a percentage of time the inverter resides in a given operating range, as specified in Equation 1.

[13] California Energy Commission and California Public Utilities Commission, “Go Solar California”, http://www.gosolarcalifornia.ca.gov/equipment/inverters.php.

Equation 1: European Efficiency Calculation

$$Euorpean\ Efficiency = 0.03 \times Eff_{5\%} + 0.06 \times Eff_{10\%} + 0.13 \times Eff_{20\%} + 0.1 \times Eff_{30\%} + 0.48 \times Eff_{50\%} + 0.2 \times Eff_{100\%,}$$

Where:

$Eff_{n\%}$ is the efficiency at n% of nominal power.

The CEC efficiency is also a weighted average, intended to be more representative of the Southwest U.S.[14] It is shown in Equation 2.

Equation 2: CEC Efficiency Calculation

$$CEC\ Efficiency = 0.04 \times Eff_{10\%} + 0.05 \times Eff_{20\%} + 0.12 \times Eff_{30\%} + 0.21 \times Eff_{50\%} + 0.53 \times Eff_{75\%} + 0.05 \times Eff_{100\%,}$$

Where:

$Eff_{n\%}$ is the efficiency at n% of nominal power.

Note the differences in weighting as well as the points where conversion efficiency is measured.

EN 50530:2010, Overall efficiency of grid connected photovoltaic inverters

This European Standard provides test procedures for the measurement of both the static and dynamic maximum power point tracking (MPPT) efficiency of inverters, which are used in grid-connected photovoltaic systems. Overall inverter efficiency is calculated based on the static MPPT efficiency and conversion efficiency. The dynamic MPPT efficiency is indicated separately.

This standard enables the rating of PV inverters on both conversion and MPPT tracking efficiency. As such, its use may serve to further differentiate the performance of PV inverters. However, research associated with this scoping effort identified only two inverter manufacturers that included EN 50530 ratings, AEG[15] and Enphase[16]. Additional research is recommended in order to better understand suitability of EN 50530 for a potential ENERGY STAR program as well as why adoption of this standard has been so low.

7. Energy Efficiency Assessment

The CEC list of eligible inverters was analyzed in order to assess ranges of PV inverter efficiencies by technology.

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[14] W. Bower, C. Whitaker, W. Erdman, M. Behnke, and M. Fitzgerald, "Performance Test Protocol for Evaluating

Inverters Used in Grid-Connected Photovoltaic Systems" p. 20, http://www.gosolarcalifornia.ca.gov/equipment/documents/2004-11-22_Test_Protocol.pdf.

[15] AEG Power Solutions, "AEG Power Solutions Solar Inverter for Megawatt Applications Achieves Shining Efficiency", http://www.aegps.com/en/investor-relations/investor-news/news-title-investor-news/article/144/.

[16] Enphase Energy, "Enphase M215", datasheet, http://enphase.com/wp-uploads/enphase.com/2011/10/Enphase-Datasheet-M215-Microinverter.pdf.

1. **Central/String Inverters**
    a. **Transformerless PV Inverters** were the most efficient, with most transformerless inverters rated between 97.5 and 98.5% efficient. SMA model SB6000 (6kW) and SB7000 (7kW) series had the highest CEC efficiency (98.5%).
    b. **High-Frequency PV Inverters** are a step lower in efficiency, making up the middle range of the CEC data set. As an example; the Solectria PVI 3000S – 7500 string inverters, for which the manufacturer claims are the most efficient transformer-isolated string inverters on the market are at 96% CEC efficiency.
    c. **Low-Frequency PV Inverters** are large, heavy, and robust due to the large transformer, but with CEC efficiencies as low as 90%, these inverters lag both high-frequency and transformerless PV inverters.
2. **Micro-inverter** CEC efficiency ranged from 89% to 96.5%. However, 210 of the 295 micro-inverters had efficiencies between 95 and 96.5%.

8. Smart Inverters

Germany, with its high penetration of solar-PV is in the process of retrofitting existing systems with smart inverter technology. These costly retrofits have become necessary in Germany in order to keep the grid stable. In order to avoid costly retrofits in the US, smart inverter efforts are underway to define and standardize communications and functionality that will enable distributed generation to enhance rather than degrade grid stability.

In Hawaii, electric rates are so high that many solar PV systems pay for themselves in 3-4 years. As a result, many homeowners have been installing solar PV systems, resulting in potential grid safety issues. In response, Hawaiian Electric Company (HECO) issued new interconnection rules in September 2013 that require pre-approval before a PV system may be interconnected. In certain cases, an interconnectivity study and costly circuit upgrades may be required.

In California, the Smart Inverter Working Group (SIWG), composed of the California Public Utilities Commission and CEC, is finalizing smart inverter requirements that would apply to all grid-connected solar inverters by October 2015. These requirements would conflict with the current versions of IEEE 1547 and UL 1741 standards that regulate grid-connected devices, resulting in different standards in California until the national standards can be updated.[17]

In addition to the Hawaii and California efforts, the Electric Power Research Institute (EPRI) is facilitating a project to enable a high penetration of distributed energy resources, including PV and battery storage, by identifying “common functions and communication protocols”. Collaborators include the US Department of Energy (DOE), the Solar Electric Power association (SEPA), and Sandia National Labs. On November 26, 2012 EPRI released a document defining a specific set of functions smart inverters should provide.[18] These common functions are being adopted into a common information model (IEC 61850) and are being mapped into relevant communications standards, including DNP3 (Distributed Network Protocol), Modbus, and Smart Energy Profile 2.x.

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[17] J. St. John, “California Closes in on Smart Solar Inverter Rules”, *Greentech Solar,* http://www.greentechmedia.com/articles/read/california-closes-in-on-smart-solar-inverter-rules.

[18] Electric Power Research Institute. “Common Functions for Smart Inverters, Version 2”, http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026809.