# Global Deployment of Solar Photovoltaics: Its Opportunities and Challenges

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***Abstract*— With the focus on environmental sustainability and energy security, policy makers and electric utility planners are looking at renewable energy both as supplements and alternatives. But such generation sources have their own challenges - primarily high variability, especially for solar and wind. This paper highlights the challenges and opportunities in grid integration of large-scale solar photovoltaic (PV) plants. Total global grid-connected PV installation exceeded 177 GW in 2014 with Germany, China, the U.S., Italy and Japan leading the way. While MW-scale solar power plants have gained significant attention as a very clean form of electricity replacing greenhouse gas-emitting fossil fuel power plants, an array of challenges regarding network operation arises from the inherent variability in output. This challenge is exacerbated when there is a high penetration of PV both in the distribution circuit and the high voltage transmission network. Potential concerns for the traditional distribution network include reverse power flow, overvoltage and voltage fluctuations, effects on voltage control devices, etc. At the transmission level the fluctuation in PV output can cause voltage stability problems. This paper addresses the growth of the PV market in different regions and briefly discusses the required interplay among external factors (like inverter functionalities, storage, demand response and revised grid standards) to provide an efficient operational strategy in the context of high PV penetrations.**

***Index Terms*— Solar PV, high PV penetration, PV industry in the U.S., PV pricing, smart inverter functions, grid codes.**

## I. GLOBAL PV GROWTH

Solar photovoltaic (PV) energy market is expanding globally at a rapid pace. On the global scale, more PV capacity was added into the generation mix since 2010 than in the previous four decades [1]. Fig. 1 shows the growth of PV throughout the globe from 2000 to 2013 [2]. As seen in this figure, the aggregate global installed PV capacity was more than 40 GW at the end of 2010. Within the next two years the 100GW mark was exceeded. In 2013, it grew to almost 138.9 GW and by 2014, more than 177 GW of PV had been installed globally. This can produce at least 200 terawatt hours (TWh) of electricity (annually) replacing over 40 large coal power plants [2, 3]. In 2014, China topped the list of countries by annual PV capacity addition with 10.6 GW while Japan followed with 9.7 GW. With 6.2 GW of PV installation the U.S. came third on this list. For total installed capacity till 2014, Germany led the pack with 38.2 GW, whereas the U.S. stood fifth (18.3 GW) [4]. As a whole, Europe secured its position as the world's leading region in terms of cumulative installed capacity, with 88 GW by the end of 2014. This represented about 49% of the world's cumulative PV capacity for 2014. The share of Europe in global cumulative PV capacity was even higher in the preceding years- 59% in 2013 and about 70% in 2012 [2]. On the other hand, Asia Pacific countries grew fast, with more than 35GW installed by 2014, an increase of 13GW from the previous year. The rest included the Americas (22GW), China (27GW), Middle East and Africa (4.5GW) and the rest of the world (2GW) [3]. A preliminary estimate for 2015 indicates that in total, 59 GW of solar PV were installed globally showing a 34% increase from the previous year (2014) [5]. As can be seen from Fig. 1, PV is growing almost exponentially everywhere with Europe leading the way. However, as Fig. 1 suggests, the growth of PV has somewhat slowed down for Europe in recent years, as the cumulative PV installation heads towards a steady level.

The global PV capacity is projected to be growing in the coming decades and is expected to be more than 450 GW by 2020 according to [6]. This medium term growth forecast considers the market trends and anticipated investments in renewable energy. Europe is expected to see a decline in the growth, but strong growth in Asia, Middle East and Africa is

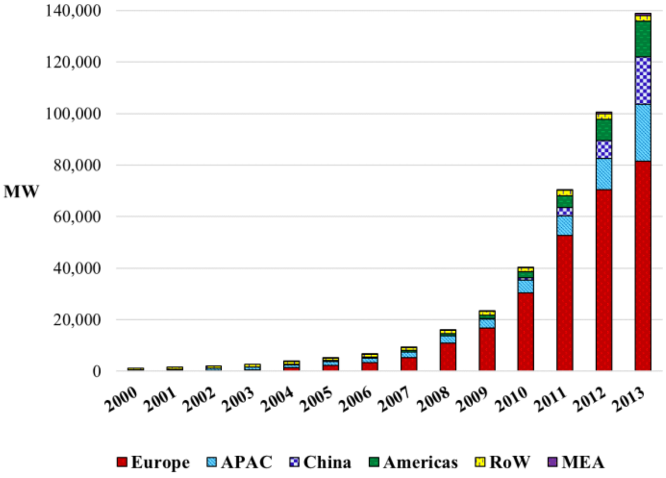

Fig. 1: Global PV cumulative installed capacity (2000-2013) [2] (APAC: Asia Pacific; MEA: Middle East and Africa; RoW: Rest of the World)

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predicted. Over the long term, PV global cumulative installed capacity can reach 4600 GW by 2050 (according to the International Energy Agency Technology Perspectives 2014), providing 6300 TWh energy per year, which is around 16% of global electricity production [1].

## II. PV INTEGRATION IN THE U.S.

The U.S. solar industry installed 7286 MW (dc) of PV in 2015, which was the largest annual addition ever and 17% more than that in 2014 [7]. Fig. 2 shows the growth of PV in the U.S. up to 2013 with both capacity additions and cumulative capacity [8]. This trend continued in the next year, 2014, when the solar PV installations reached 6201 MW (dc) [9]. By the end of 2015, the cumulative U.S. solar PV capacity had crossed the 25 GW mark. Fig. 3 shows the upward trend in annual solar PV installations in the U.S. from 2000 to 2013 with constituent sectors [10]. As shown in Fig. 3, utility-scale PV constitutes the majority of the U.S. solar market in recent years. The utility sector gained a strong ground in the U.S. around 2010 and has been showing consistent growth since then. The residential PV installations also showed major growth in 2015 and accounts for 29% of the U.S. solar market [7].

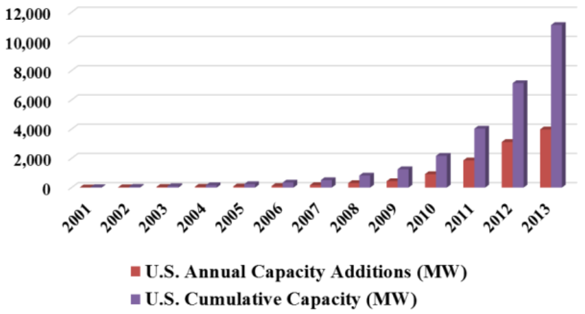

Fig. 2: U.S. grid-connected PV capacity [8]

Utility-scale solar projects are mostly located in south-western parts of the U.S. The annual insolation (measured with direct normal irradiance in kWh/m$^2$/day) is the highest in these states and also the state level policies encourage the deployment of utility-scale projects [11]. Among large-scale concentrating and thermal PV projects (> 5 MW (ac)), crystalline silicon (C-Si) modules had been widely used either with tracking devices or fixed installations. Thin-film modules (mostly Cadmium Telluride or CdTe) were also used by utility-scale projects, but typically with fixed-tilt arrangements prior to 2014 [11].

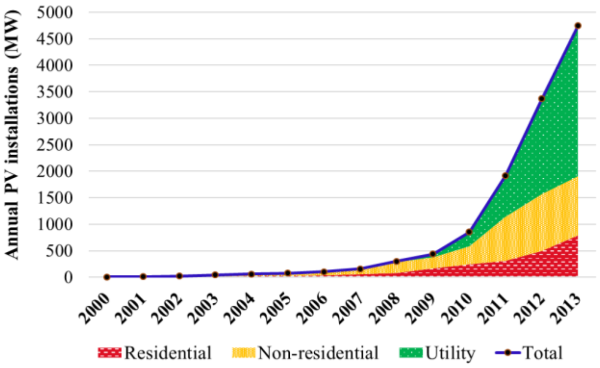

Fig. 3: U.S. annual solar PV installations in residential, non-residential and utility sectors [10]

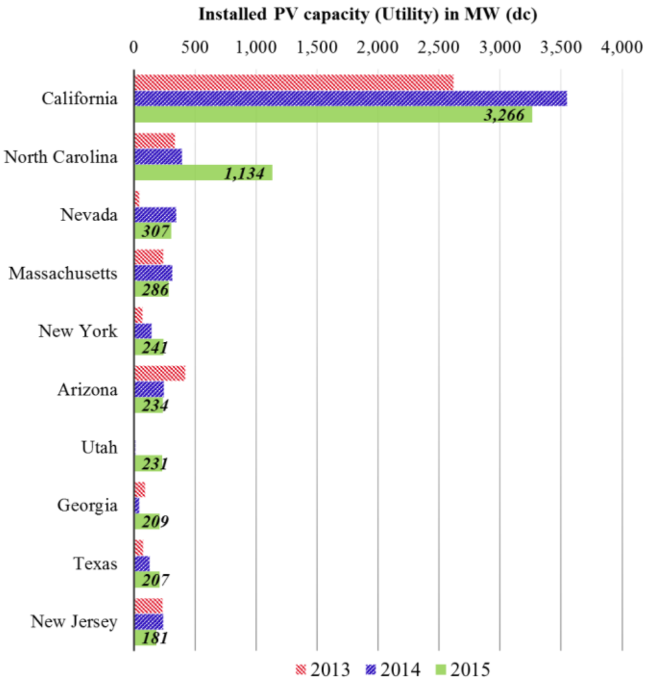

Fig. 4: State rankings for 2015 solar PV annual capacity additions, and installations in 2013-14 period [12]

Among the U.S. states, California continues to lead the solar market due to the abundant solar energy and supportive solar policies. Fig. 4 shows the state-wise ranking with regard to PV installation (annual utility additions) for 2013-15 [12]. The top 10 states are included in Fig. 4 according to the rank derived for 2015 annual capacity installations. As Fig. 4 shows, California installed 3266 MW of PV in 2015 [12]. Nearly 57% of these new PV installations in 2015 were in utility sector, 31% were in residential and the rest were non-residential or commercial applications [13]. California keeps leading the nation as more projects are coming online. For example, Desert Sunlight was completed in 2015 by First Solar with a capacity of 550 MW [14]. Fig. 5 shows the state rankings for cumulative PV capacity (till second quarter of 2015) and California claims the top position [15]. Arizona being one of the sunniest states, had a

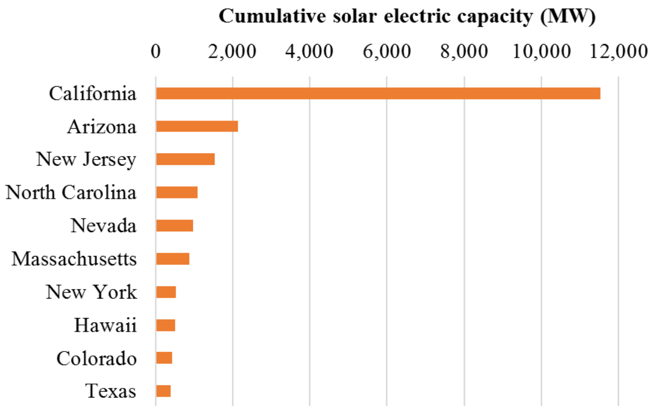

Fig. 5: State rankings for 2015 (Q2) solar PV- cumulative capacity [15]

remarkable growth in its solar market in recent years, and is ranked as the second in terms of installed PV capacity (Fig. 5). Nonetheless, owing to the public debate on the benefits of solar, imposition of a net metering charge and elimination of the incentives, the market growth decelerated in 2014 [16]. Till September 2015, New Jersey had 1524 MW of solar installations, making it the third on this list [17]. North Carolina too is showing quick growth, partly due to the state's Renewable Energy and Energy Efficiency Portfolio Standard (REPS). North Carolina installed 1134 MW of solar capacity in 2015, making its installed capacity surpass 2000 MW by the end of 2015 [18]. Nevada is evolving as another top state for solar opportunity with 1240 MW (as of 2015) of cumulative installed capacity [19].

## III. PRICING OF PV INSTALLATIONS

The explosive growth of PV is further expedited with the falling price of PV installations. Fig. 6 shows the price decline for utility-scale PV projects since 2010 [20] in the U.S. The average price per kWh of utility-scale PV projects has dropped almost 50% from 2010 to 2013 (from 21.4 cents/kWh to 11.2 cents/kWh). These projects include large, centralized PV systems that are directly tied to the grid. As seen in this figure, the cost reduction is mostly achieved by lowering of the module costs. The goal is to lower the net price further and reach $0.06/kWh (equivalent to $1.00/Wp dc) by 2020. This cost target is set by the U.S. Department of Energy (DoE) and is designed to make solar a cost-competitive renewable energy source compared to traditional fossil-fueled plants.

A pathway to PV system price reductions is delineated in Fig. 7 for utility-scale PV systems with one-axis tracking technology [21]. This price reduction was derived from the 2010 benchmark of $4.40/Wp dc. As per [21], the National Renewable Energy Laboratory (NREL) estimated that over the next decade, an evolutionary module price reduction (projected to be ~$1.1/Wp) would contribute less to reduce the costs of utility-scale systems compared to residential/commercial PV systems. Better module efficiency (from ~14.5% to 21%) would provide $0.57/Wp cost reduction for these large PV systems. Inverter prices for utility-scale applications have also dropped significantly in recent years and is anticipated to

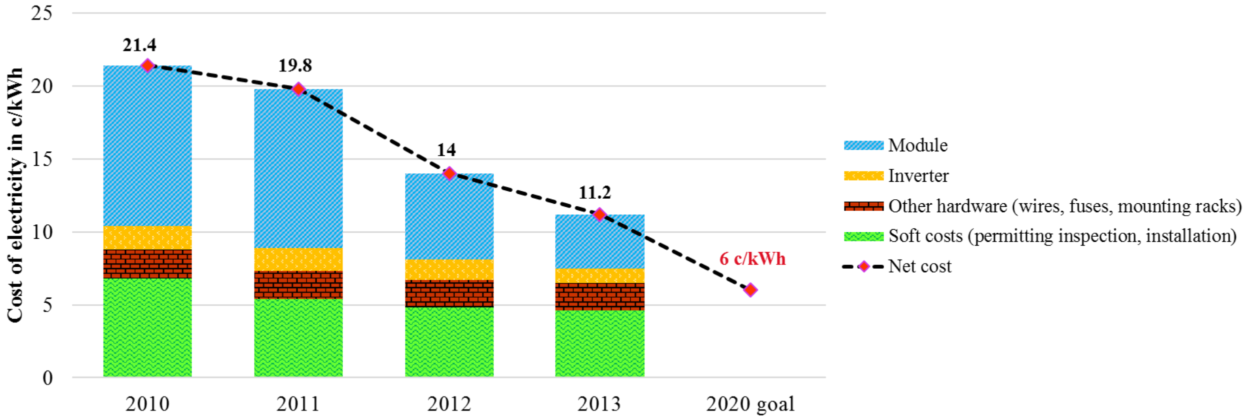

Fig. 6: Price drop of utility-scale solar PV projects [20]

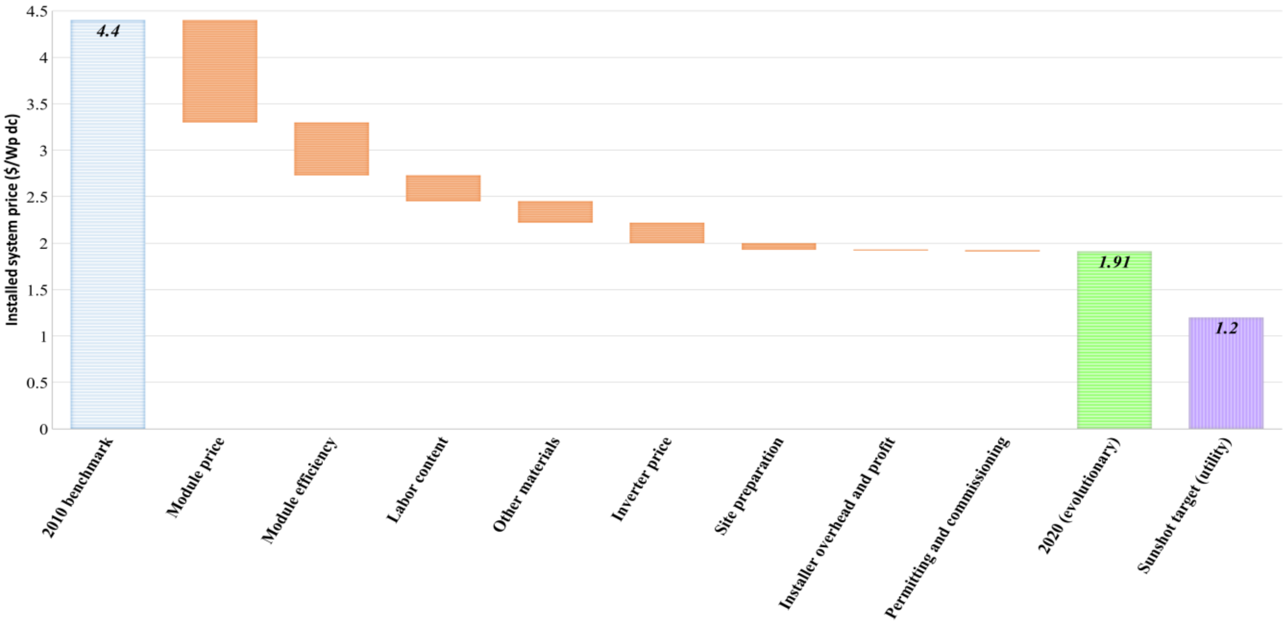

Fig. 7: Evolutionary utility-scale (one-axis tracking) PV system price reductions from 2010-2020 & modified DoE target for 2020 [21]

approach ~\$0.10/Wp by the end of the decade. Because the U.S. DoE Sunshot target is set for fixed-axis PV systems (\$1.00/Wp dc), Fig. 7 includes the modified target for PV systems with one-axis tracking (~\$1.20/Wp dc). This modification considers the net benefit for mounting C-Si modules on one-axis tracking architecture. These estimates by NREL suggest that the module price and other soft costs have to be reduced by technological innovations if the DoE target is to be achieved by 2020.

## IV. OPERATIONAL ISSUES AND TECHNICAL SOLUTIONS

Some of the operational issues regarding PV integration arise from the impacts of growing PV penetration in the grid [22]:

### *A. Impacts of growing PV penetration*

- Reverse power flow:

When PV generation is high, the power flow direction through lines might get reversed as it can offset some of the total feeder load, and feed power to neighboring feeders or to transmission network at daytime. This situation creates operational hazards for equipment which are chiefly designed to handle unidirectional flow, like many of the overcurrent protection devices and line voltage regulators.

- Overvoltage and voltage fluctuations:

The PV generation reduces the feeder load and in return increases bus voltages. But at times of cloud transients, significant voltage fluctuations can be observed throughout the system. Both of these situations become more problematic as the PV penetration grows. The extent of voltage fluctuations is not only a function of the PV generation but also dependent on the PV plant location and the network configuration.

- Effects on voltage control devices:

In a traditional distribution network, the voltage rise due to PV generation directly impacts the operation of voltage control devices like On-Load Tap Changer (OLTC), Switched Capacitor Banks (SCB) and line Voltage Regulators (VR). All of these devices inherit operational delays due to their control techniques. However, due to the higher frequency of PV-induced voltage fluctuations, these devices need to operate more frequently than usual to keep the network voltage within prescribed limits.

### *B. Required inverter functionalities*

To combat these issues, advanced inverter functionalities are being developed which can help seamless PV integration. For example, variable reactive power injection and active power curtailment can reduce overvoltage or voltage fluctuations induced by PV output intermittency [23]. Some common smart inverter functions are briefly described here [24]:

- Low/High Voltage Ride-Through (L/HVRT):

This function is envisioned in a way so that the inverter can provide a variable mechanism through which it may configure a general Low/High Voltage Ride-Through (L/HVRT) behavior. L/HVRT functionalities are to be implemented with user-configurable X (duration)-Y (voltage parameter) arrays. Fig. 8 describes examples of LVRT and HVRT areas created by configurable curves. L/HVRT functions are defined with two piecewise-linear curves (each)- *Must disconnect* (in blue in Fig. 8: LM1-LM5 or HM1-HM5), and *Must stay connected* (in orange in Fig. 8: LC1-LC6 or HC1-HC4). *Must disconnect* curves are assumed to extend downward or upward from the first point (LM1 or HM1) and horizontally to the right from the last point (LM5 or HM5). *Must stay connected* curves are assumed to pan horizontally to the left from the first point (LC1 or HC1 marking zero second) and to the right from the last point (LC6 or HC4). The set of upper and lower curves (HC-HM, and LC-LM) are defined as such so that no ambiguity or overlapping occurs and the inverter is *allowed to stay connected or can disconnect* in between specified lines. Although the example shown in Fig. 8 shows only stair-step transitions, diagonal or sloping settings can also be used. Additional parameters (for example, maximum service voltage level and short-term interruption limit) need to be defined when the inverter reconnects after a voltage event.

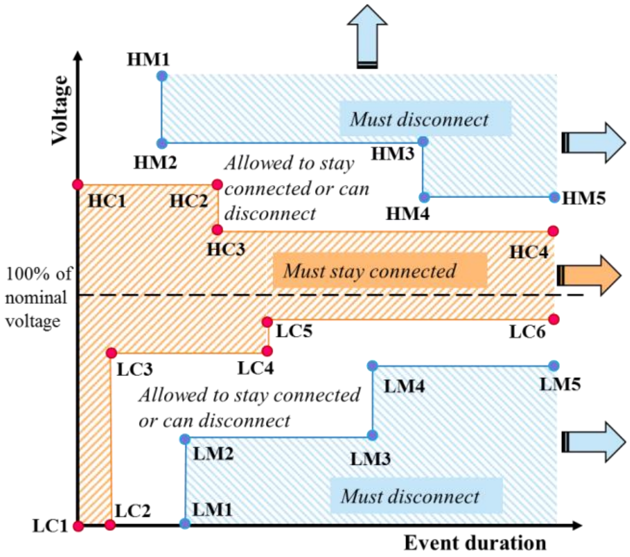

Fig. 8: Example LVRT and HVRT areas created by four configurable curves [24]

- Maximum generation limit:

This function operates as a control and establishes a real power limit that the inverter can deliver to the grid at the inverter interconnection point irrespective of the instantaneous generation. Electric Power Research Institute (EPRI) proposed that the maximum generation level function should be percentage based, according to the peak generation capability of the device. An example function setting is given in Fig. 9 [24]. Time window is used to define the duration over which a

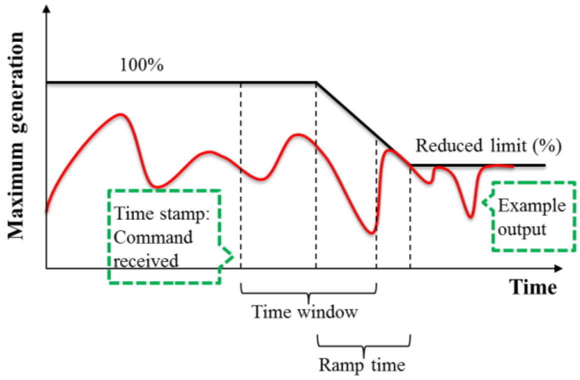

Fig. 9: An example function setting for maximum generation limit [24]

new setting would take effect whereas ramp time expresses the duration over which the new limit is placed in a linear fashion. Read & Set Maximum Generation Level commands are used to specify the maximum generation level as a percent of peak generation.

- Volt-VAR function:

EPRI proposed that a desired Volt-VAR behavior of the inverter should be configured using a two-dimensional array of points (voltage and required reactive power) as explained in Fig. 10 [24]. A variable number of points (4 points in the example of Fig. 10: Z1-Z4) defining a piece-wise linear curve of the desired Volt-VAR behavior would be the input for this function. "Available VARs" as seen in Fig. 10, implies the reactive injection/consumption level the inverter is capable of providing at any moment, without sacrificing its real (Watts) output. In this example setting, the VAR level is assumed to remain constant for voltages below Z1 output (at Q1) and above the highest voltage point for Z4 (at Q4). To set up the ramping functions, at least two points (Z2 with V2 and Z3 with V3; both with zero reactive power) are required.

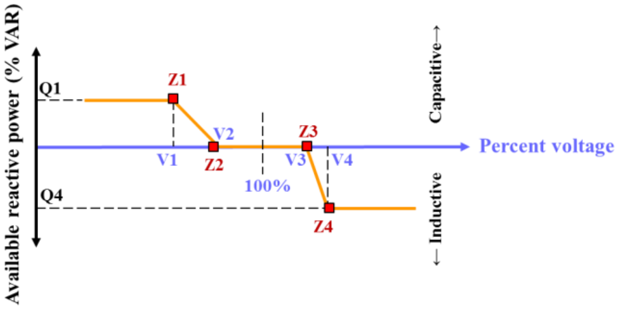

Fig. 10: An example of Volt-VAR behavior function [24]

## C. *Revised grid codes*

Inverters were originally designed and sold with real power or kW rating rather than its apparent power or kVA rating. This unity power factor operation was mandated by interconnection standards. But the rapid growth of renewables led to the need of reactive regulation from their end and subsequently, existing standards (for example, IEEE 1547a [25]) have been revised to include the reactive power requirements applicable for distributed resources. Another example is set by Germany which updated its VDE (Verband der Elektrotechnik, Elektronik und Informationstechnik (The Association for Electrical, Electronic & Information Technologies)) code of practice (VDE-AR-N 4105) effective since January 2012 [26-27]. Under this code, PV plants connected to the LV grid needs to follow the requirements of phase balancing, frequency-based power reduction, reactive power control, inverter reconnection conditions, output power control etc.

The Frequency-based Power Reduction function is designed in a way so that PV systems or other controllable generators can meet the frequency requirements set by VDE-AR-N 4105. Fig. 11 describes this inverter function for a 50 Hz system [28]. This function states that, if the frequency remains in the range of 50.2- 51.5 Hz, PV systems need to decrease/increase the active generation with a gradient of 40% of the instantaneously available power, $P_m$, for every Hz of frequency increase/decrease. Apart from that, if network frequency is higher than 51.5 Hz, the PV system must disconnect immediately from the network (safety shutdown). Also, the PV system may only be connected/re-connected to the network if the service voltage is within the range of 85%-110% of nominal voltage and the network frequency is within the tolerance range of 47.5-50.05 Hz. These ranges for voltage and frequency are to be evaluated for at least a period of 60 seconds [28-29].

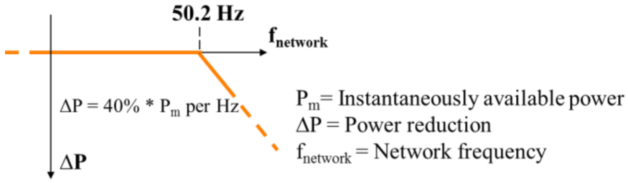

Fig. 11: Active power reduction for PV systems in the case of over-frequency [28]

## D. *Demand response and storage:*

In addition to revised grid codes and advanced inverter functionalities, storage and demand response can assist in increasing the PV hosting capacity. These components can help in local consumption and thus lessen the burden on regional MV/LV grids. This mechanism of self-consumption limits the distribution of fluctuating energy throughout the grid [30]. Recent trends encourage on-site self-consumption for PV owners; for example, the Renewable Energy Sources Act (Erneuerbare Energien Gesetz (EEG)) levies on self-consumption in Germany [31]. Self-consumption can be increased using Demand Response (DR) which changes the pattern of the load curve. DR decreases balancing needs and thus large electricity consumers who own PV systems can provide better grid services. Storage can also play a vital role in increasing the PV penetration by shifting excess production when the demand is high, especially during peak consumption periods. Although complete self-consumption is ideally feasible without storage, storage integration can assist in making PV more competitive. Energy storage can help electricity savings surpass the revenues earned by selling the electricity on the wholesale market. Storage can also smoothen generation peaks and thus defer reinforced investments in T&D sectors. However, the cost of energy storage needs to be considered to find out if it provides more monetary benefits to the owner than operating PV alone [32-33].

# V. SUMMARY

This paper summarizes the global growth of solar photovoltaics till now and also discusses projected growth in the coming years, and the associated challenges. Solar PV is widely acknowledged as the fastest-growing renewable energy industry. Utility-scale PV systems are rapidly growing throughout the globe, especially in the U.S., China and India. Growing PV penetrations can impact the grid operation and in turn hinder the expansion of solar market. Grid codes are being revised to accommodate the high PV penetration scenario. Auxiliary methods like smart inverter functionalities, integration of storage and demand response can benefit solar integration and at the same time formulate additional challenges. Through further research, these are expected to help the solar market expand beyond the projections in near future.

## REFERENCES

[1] International Energy Agency, "Technology Roadmap: Solar Photovoltaic Energy," Sep 2014. Available: https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarPhotovoltaicEnergy_2014edition.pdf

[2] Global Market Outlook 2014-2018, SolarPower Europe, 2015. Available: http://www.cleanenergybusinesscouncil.com/site/resources/files/reports/EPIA_Global_Market_Outlook_for_Photovoltaics_2014-2018_-_Medium_Res.pdf

[3] Global Market Outlook for Solar Power: 2015-2019, SolarPower Europe, 2016. Available: http://www.solarpowereurope.org/insights/global-market-outlook/.

[4] International Energy Agency (IEA), Snapshot of Global PV Markets, Photovoltaic Power System Programme (PVPS) Report, 2014.

[5] M. Munsell, "GTM Research: Global Solar PV Installations Grew 34% in 2015", Greentech Media, Jan 2016. Available: http://www.greentechmedia.com/articles/read/gtm-research-global-solar-pv-installations-grew-34-in-2015

[6] "Renewable Energy: Medium-Term Market Report, Market Analysis and Forecasts 2020", International Energy Agency, 2014.

[7] U.S. Solar Market Sets New Record, Installing 7.3 GW of Solar PV in 2015, Solar Energy Industries Association, Feb 2016. Available: http://www.seia.org/news/us-solar-market-sets-new-record-installing-73-gw-solar-pv-2015

[8] G. Barbose, S. Weaver, and N. Darghouth, "An Historical Summary of the Installed Price of Photovoltaics in the United States from 1998 to 2013", Lawrence Berkeley National Laboratory & US DOE Sunshot Program, Sep 2014.

[9] Solar Market Insight Report: 2014 Year in Review, GTM research and Solar Energy Industries Association, Mar 2015.

[10] Solar Market Insight Report: 2013 Year in Review, Solar Energy Industries Association, Mar 2014. Available: https://www.seia.org/research-resources/solar-market-insight-report-2013-year-review

[11] M. Bolinger, and J. Seel, "Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States", Lawrence Berkeley National Laboratory (LBNL) & US DOE Sunshot Program, Sep 2015.

[12] U.S. Solar Market Insight: 2015 Year-in-Review (Executive Summary), GTM research and Solar Energy Industries Association, Mar 2016.

[13] Solar spotlight: California; Solar Energy Industries Association, 2015. Available: http://www.seia.org/sites/default/files/CA%20State%20Fact%20Sheet_2.26.2016.pdf

[14] California Clean Energy Tour: Desert Sunlight Solar Farm, California Energy Commission, 2016. Available: http://www.energy.ca.gov/tour/desertsunlight/

[15] Solar Energy Facts: Q2 2015, Solar Energy Industries Association (SEIA), 2015. Available: http://www.seia.org/sites/default/files/Q2%202015%20SMI%20Fact%20Sheet.pdf

[16] State solar policy: Arizona; Solar Energy Industries Association (SEIA), 2015. Available: http://www.seia.org/state-solar-policy/arizona.

[17] New Jersey Solar, Solar Energy Industries Association (SEIA), 2015. Available: http://www.seia.org/sites/default/files/NJ%20State%20Fact%20Sheet_9.9.15.pdf

[18] State solar policy: North Carolina; Solar Energy Industries Association (SEIA), 2015. Available: http://www.seia.org/state-solar-policy/north-carolina

[19] Solar spotlight: Nevada; Solar Energy Industries Association (SEIA), 2015. Available: https://www.seia.org/sites/default/files/NV%20State%20Fact%20Sheet_9.9.15.pdf

[20] E. R. Pierce, "Progress Report: Advancing Solar Energy Across America", U.S. Department of Energy, Feb 2014. Available: http://energy.gov/articles/progress-report-advancing-solar-energy-across-america

[21] A. Goodrich, T. James, and M. Woodhouse, "Residential, Commercial, and Utility-Scale Photovoltaic (PV) System Prices in the United States: Current Drivers and Cost-Reduction Opportunities", Technical report, NREL, Feb 2012.

[22] F. Katiraei, J.R. Agüero, "Solar PV Integration Challenges", *IEEE Power and Energy Magazine*, Vol. 9, No. 3, pp. 62-71, May/Jun 2011.

[23] S. Ghosh, S. Rahman, and M. Pipattanasomporn, "Local distribution voltage control by reactive power injection from PV inverters enhanced with active power curtailment," *2014 IEEE PES General Meeting*, National Harbor, MD, Jul 2014, pp. 1-5.

[24] "Common Functions for Smart Inverters, Version 3", EPRI, Feb 2014. Available: http://www.epri.com/abstracts/ Pages/ProductAbstract.aspx?ProductId=000000003002002233).

[25] *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems - Amendment 1*, IEEE Std 1547a-2014 (Amendment to IEEE Std 1547-2003), pp. 1-16, May 2014.

[26] VDE-AR-N 4105, "Generators connected to the low-voltage distribution network: Technical requirements for the connection to and parallel operation with low-voltage distribution networks", VDE Application Guides, Aug 2011. Available: http://www.vde.com/en/dke/std/VDEapplicationguides/Publications/Pages/VDE-AR-N4105.aspx

[27] PV grid integration: Backgrounds, requirements, and SMA solutions, TechnologyCompendium 3.4, SMA, May 2012. Available: http://files.sma.de/dl/10040/PV-Netzint-AEN123016w.pdf

[28] H. Berndt, M. Hermann, H. D. Kreye, R. Reinisch, U. Scherer and J. Vanzetta, "Transmission code 2007: Network and System Rules of the German Transmission System Operators", VDE, August 2007. Available: https://www.vde.com/de/fnn/dokumente/documents/transmissioncode%202007_engl.pdf

[29] The 50.2 Hz problem: Controlling active power in the event of overfrequency in generators connected to the low-voltage distribution network, VDE, 2011. Available: http://www.vde.com/en/fnn/pages/50-2-hz.aspx

[30] The self-consumption bonus: Information and details regarding the self-consumption of solar energy, SMA, Jul 2010. Available: http://www.sma.de/en/partners/knowledgebase/the-self-consumption-bonus.html

[31] H. Wirth, "Recent Facts about Photovoltaics in Germany", Fraunhofer ISE, Apr 2016. Available: https://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/recent-facts-about-photovoltaics-in-germany.pdf

[32] International Energy Agency Photovoltaic Power System Programme (IEA-PVPS), Review and Analysis of PV Self-Consumption Policies, 2016. Available in: http://iea-pvps.org/index.php?id=353.

[33] Connecting the Sun: Solar Photovoltaics on the road to large-scale grid integration, European Photovoltaic Industry Association, Sep 2012.

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