High Penetration PV in Local Distribution Grids Outcomes of the IEA PVPS Task 14 Subtask 2

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ABSTRACT: During the past four years, national experts from thirteen institutions around the world have worked together within the International Energy Agency (IEA) PVPS Task 14 Subtask 2 – High Penetration PV in Local Distribution Grids. The main aim of this collaboration was to identify industry's best practices for achieving high penetration levels of PV integration on the distribution grid in a technically sound and economically efficient manner. Based on an analysis of the different national regulatory frameworks for the interconnection of PV systems into distribution grids implemented around the world to date, and the lessons learned from selected national high penetration PV case-studies, best-practice examples have been established which outline the crucial technical milestones leading towards successful global large scale high PV penetration scenarios.

Keywords: Photovoltaic, Distribution Grid, Grid Integration, International Energy Agency

1 INTRODUCTION

In 2013, 38.4 GWp of PV systems were installed globally, adding up to a world-wide installed PV capacity of 138.9 GWp[1] by the end of 2013 [1]. Top driving markets for new PV installations were China (11.8 GWp), followed by Japan (6.9 GWp) and the USA (4.8 GWp) [1]. Germany, formerly the world's biggest market for PV installations, fell back to fourth place with 3.3GWp of PV capacity installed in 2013, but still remains Europe's top market [1].

According to the European PV Industries Association's (EPIA) recently published "Global Market Outlook" [1] this trend reversal – China, Japan and the USA replacing Europe's PV national markets leadership– is expected to consolidate in the next years.

As the share of solar electricity in the global electricity mix continues to grow, it becomes increasingly important to understand the technical and economic challenges associated with high PV penetration scenarios. There is a particular need for international R&D collaboration in order to collate and disseminate worldwide knowledge about high penetration levels of PV.

The International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D agreements established within the IEA. Since its establishment in 1993, PVPS task-participants have been conducting a variety of joint projects in the application of photovoltaic conversion of solar energy into electricity. The main goal of Task 14[2] is to promote the use of grid-connected PV as an important source of energy in electric power systems at higher penetration levels - levels that may require additional efforts to effectively integrate them into the electricity industry. The particular aim of these efforts is to reduce technical barriers for achieving high penetration levels of distributed renewable systems.

During the past four years, national experts from thirteen institutions from around the world have worked together within Subtask 2 – High Penetration PV in Local Distribution Grids – in order to identify and share best practices for a technically and economically improved distribution grid integration of PV. Subtask 2 is one of the key parts of a broader IEA PVPS Task 14 work program including local PV supply-demand matching (Subtask 1), system level PV integration studies (Subtask 3) and upcoming PV inverter techniques (Subtask 4)

This paper summarizes the outcome of the IEA Task 14 Subtask 2 from the past four years.

[1] Status update July 2014: World-wide installed PV capacity more than 150 GW [2]

[2] http://www.iea-pvps.org/index.php?id=58#c92

2 TRANSITION FROM UNI- TO BI-DIRECTIONAL DISTRIBUTION GRIDS

A simplified definition of different PV penetration levels can be established according to the directionality of the net power flows at the point of interconnection between distribution system operator (DSO) and transmission system operator (TSO). The electricity supply system of every country that is aiming at increasing its share of PV on the total electricity mix will typically face three different development stages:

Stage 1: Low/ medium PV penetration in a few distribution grids – Local consumption still exceeds local generation (uni-directional distribution grids)
Stage 2: High PV penetration in few distribution grids – Local generation can exceed local consumption (bi-directional distribution grids)
Stage 3: High PV penetration in many distribution grids – PV as a major electricity source

The technical and economic challenges that are associated with this transition process can be roughly divided into local (customer and distribution network) and systemic (e.g. on a balancing area or national scale) issues. Local challenges of high PV penetration scenarios effect the operation of distribution grids whereas systemic challenges are having an impact on the operation and stability of the national transmission system. Both levels have to be addressed by research, development and demonstrations in order to find solutions for a smooth transition from uni-directional to bi-directional distribution grids in the context of national high PV penetration scenarios.

Stage 1 (uni-directional distribution grids): This stage constitutes the beginning of national PV deployment. A small number of distribution grids (i.e., distribution substation including downstream distribution system) experience a low and medium level PV penetration, respectively. This means that a small number of circuits, predominantly in rural areas, will show reverse power flows caused by PV generation during times of high solar irradiance. However, the distribution systems are still load-dominated, which means that no reverse power flows towards the upstream transmission system occur. The distribution system operator will experience few voltage and loading issues associated with the increasing PV penetration limited to the interconnected distribution feeder. On the transmission system level, no technical effects caused by PV power generation are generally observed.

Stage 2 (bi-directional distribution grids): At this stage, a small number of distribution grids with high local PV penetration exist. In contrast to stage 1, reverse power flows from the distribution system towards the transmission system can be observed quite frequently. Within these highly PV penetrated distribution grids the installed PV capacity exceeds the local peak load many times over, leading to potentially very significant over-voltage and over-loading issues. Grid reinforcement becomes necessary in order to host the installed PV capacity properly. The increased (reverse) power flows and the restructuring of the grid lead to a changing reactive power behavior of the distribution system. In detail, the reactive power consumption by conductors during times of high solar irradiance increases, due to increased active power flows. Concurrently reactive power generation by conductors at night increases, due to reinforcement (e.g., additional cables or substitution of overhead lines by underground cables). Often, these highly PV penetrated distribution grids will be identified as project regions to study the effects of high local PV penetration on the distribution system operation.
In parallel, the impact of bulk PV penetration on the transmission system operation can be observed for highly penetrated regions. This includes reverse power flows from distribution grids into the transmission grid which lead to an increased demand in re-dispatch of conventional power plants and revised procedures for congestion management.

Stage 3 (national high PV penetration): Stage 3 marks the final stage on the way towards PV as a major electricity source. The stage is achieved, if the overall power system is highly penetrated by PV systems. The focus of PV grid integration must also now be set on transmission system operation, including the provision of ancillary services from dispersed generation. Mature technical solutions for PV grid integration are required to cope with decreasing fault-currents on high and extra-high voltage levels as well as potentially severe frequency and voltage stability issues.

The three penetration stages are depicted in Figure 1. Following the red path through these stages shows typical observations of distribution and transmission system operators for different PV penetration scenarios.

Note: For a technically reliable and cost-effective transition through these three stages it is extremely important to have an effective technology and regulatory framework ready for when it is effectively needed. From an early stage (i.e., stage 1) onwards this requires a continuous adaption of network codes and laws in regards to high national PV penetration scenarios. Neglecting the process of early adaptation will most likely result in high grid integration costs as retrofitting of existing PV systems will become necessary (compare recommendations in Section 3).

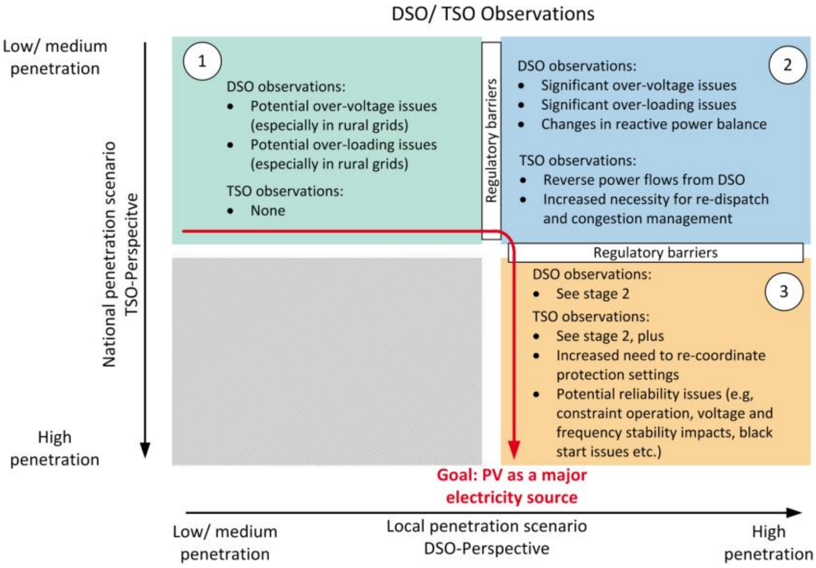

Fig.1 : DSO and TSO observations according to different local and national PV penetration level.

Figure 2 shows a good example for the transition from a uni- to a bi-directional power flow pattern of a certain distribution grid, due to a continuously increasing local PV penetration.

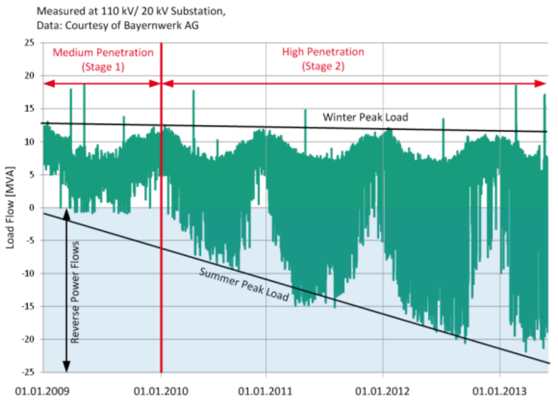

Fig. 2: Power flow, measured at a 110kV/ 20kV substation in the service area of the Bayernwerk AG, Germany. This particular distribution grid section deals as a German case-study with IEA Task 14.

3 STATE-OF-THE-ART AND ADVANCED TECHNIQUES FOR THE TRANSITION FROM UNI- TO BI-DIRECTIONAL DISTRIBUTION GRIDS

This section deals with the transition from stage 1 to stage 2 and outlines technical services that can be offered by state-of-the-art PV systems and novel distribution network assets in order to integrate PV in a technical effective and economic efficient manner.

Figure 3 depicts the bandwidth of possible technical services state-of-the-art PV and PV-battery systems could theoretically offer. For standard grid-connected PV applications without additional storage it is the inverter that enables most of the active and reactive power control capabilities.

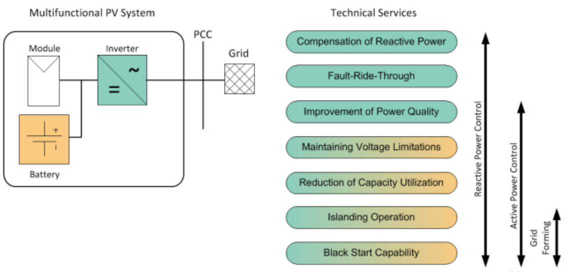

Fig. 3: Technical services which can theoretically be offered by state-of-the-art PV and PV-battery systems [3].

3.1 REACTIVE POWER CONTROL CAPABILITIES

Initially, reactive power provision via PV inverters was established to mitigate high voltage magnitudes caused by reverse power flows. Numerous studies (e.g. [4] - [10]) highlighted the technical potential of reactive power for increasing a grid's hosting capacity, although the technical effectiveness decreases with lower voltage levels.

As of today, the reactive power capabilities of PV inverters (especially the so-called Q@night capability [11]) have started to attract the interest of DSOs in the context of reactive power compensation. Reactive power provision can be classified in static reactive power provision and dynamic reactive power provision.

Static reactive power provision: In many IEA-PVPS Task 14 member countries, static reactive power provision capability is required from PV systems, however its practical utilization is up to the local DSO, e.g. [12], [13]. Typical applications for residential scale PV systems focus on autonomous control (i.e., without additional information and communication interface to the DSO) of reactive power in order to mitigate voltage rise. The commonly used methods include the provision of a fixed power factor (*cosφ = const.*) or a power factor as function of the current active power feed-in: *cosφ = f(P)*. Utility scale PV systems typically come with a remote control interface that allows DSOs to transmit reactive power set values to the PV plant.

Voltage dependent reactive power provision (so-called Volt/VAr control or Q=f(V)) is considered being more advanced as it provides reactive power based on the locally measured voltage magnitude of the inverter. Nevertheless, at the moment the use of this strategy is mostly limited to selected grids and demonstration regions, since the possible effects and critical interaction of multiple generators are not fully understood today. Various research projects in Task 14 member countries are currently investigating the technical performance of such a control strategy with a strong focus on local stability issues, e.g. [14] - [16].

Dynamic reactive power provision: In addition, grid codes in some Task 14 member countries require larger PV systems and other generating units to inject reactive current in order to support the grid during voltage dips/sags [12], [17]. This technical service is also known as “Fast reactive current injection” and is one part of the Low-Voltage Ride Through Capability (LVRT). Depending on the magnitude and duration of the voltage dip, the inverter is required to stay connected, inject reactive current or is allowed to disconnect based on a characteristic that is part of each country’s technical specification.

3.2 ACTIVE POWER CONTROL CAPABILITIES

The idea of controlling the active power output of PV systems to provide technical services to is gaining in importance. Typically, active power control – without storage it is actually limited to active power reduction – is a common tool for DOSs to overcome short-term network congestions by reducing the power output of PV systems and allow for a higher generation capacity to be connected under normal conditions.

Active power control by PV inverters: The simplest form of active power control at the PV system’s point of common coupling is to solely use the PV inverter for active power reduction. State-of-the-art solutions encompass fixed curtailment, either controlled directly at the inverter output or at the PV system’s point of common coupling (e.g., the former 70% cap as required by the German EEG from 2012) or DSOs sending active power feed-in limitation set values via a remote control interface. Analogous to the reactive power based Volt/VAr control also an active power based Volt/Watt control has its benefits over fixed limitations. On the one hand Volt/Watt control reduces active power only when technically required (in case of over-voltages) and hence reduces the overall active power losses over all PV system within a certain grid section [6], [18]. On the other hand Volt/Watt control will discriminate those PV systems with technically unfavorable points of common coupling. In such a case, approaches for the compensation of lost energy need to be developed.

Increasing self-consumption and intelligent load-management: If PV power reduction is not the preferred solution, methods for increasing the PV self-consumption might be an option. By definition, self-consuming PV electricity reduces the power feed-in at the point of interconnection and hence can be used to mitigate over-voltage issues, if applied accordingly (i.e., if self-consuming during peak PV output times and if the same phase is used for load and generation [19]).

PV storage systems: Another way of increasing PV self-consumption is using local storage for surplus PV energy. Depending on the energy management of the PV battery system additional ancillary services can be provided whilst minimizing feed-in losses (compare Figure 3 and Figure 4). The interested reader should refer to [20] for further reading on local grid support by PV battery systems.

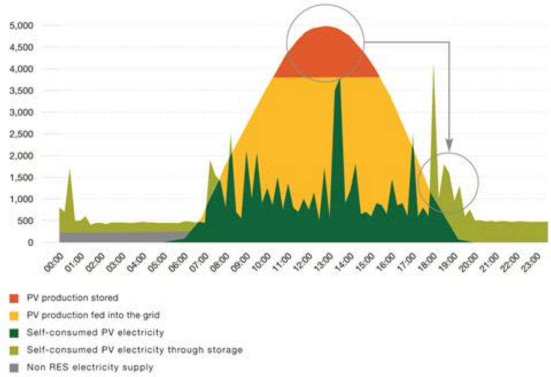

Fig. 4: PV peak-shaving using storage at household level [21].

3.3 NOVEL ASSETS AND GRID PLANNING PRINCIPLES FOR DSOs

Besides technical services offered by PV systems, additional novel distribution network assets and revised grid planning principles can help to improve PV grid integration compared to the often cost intensive ways of traditional grid reinforcements (e.g., additional cable capacity, exchange of transformer). In the following, a brief overview on existing best-practice solutions which are applied in the Task 14 member countries is given. More detailed information can be found in the case-study collection of IEA Task 14 Subtask 2 [22] and the corresponding management summary [23]:

On-load tap changer (OLTC): For HV/MV as well as for MV/LV transformers. While HV/MV OLTCs have seen wide use in many Task 14 member countries the use of additional MV/LV OLTCs are a novel asset that is considered as a promising solution to solve severe over-voltage issues at LV level by DSOs across continental Europe.

Booster transformer: Either MV/MV or LV/LV transformers for stabilizing the voltage along long feeders with voltage problems.

VAr-Control: Static VAr compensators (SVC), STATCOM or hybrid solutions can be used for reactive power compensation and/ or voltage control.

Closed-loop and meshed operation: Can be used to increase the short-circuit power within a grid and hence reduce the effect of dispersed power feed-in on voltage magnitudes. Closed-loop operation is common practice at the HV level and above, but it could affect existing protecting settings if applied at MV and LV level and increase the complexity of standard network operation.

3.4 COST-BENEFIT ANALYSES

Choosing an appropriate technology from the above mentioned solutions is subject to its technical feasibility, the regulatory framework and its economic reliability.

In order to assess the economic reliability of different solutions for high PV penetration scenarios, various cost-benefit analyses were performed in different research projects, e.g. [6], [18] - [20], [24] – [26]. One example is based on the German case-study within Task 14 as described in [6] and [22]. The cost-benefit analysis compares different autonomously operating voltages control strategies, provided by PV inverters and MV/LV transformer with OLTC, for two real LV grids with already high local PV penetration (the grid can be assigned to stage 2). The applied methodology is described in [6]. Figure 5 compares the resulting net present value for applying different voltage control strategies assuming a constant increase in the local PV penetration over the period of 10 years. The figure clearly shows that the application of voltage control strategies significantly reduces the grid integration costs of PV compared to traditional grid reinforcement strategies (additional cables and transformer exchange), even if active power feed-in of PV systems has to be reduced temporarily.

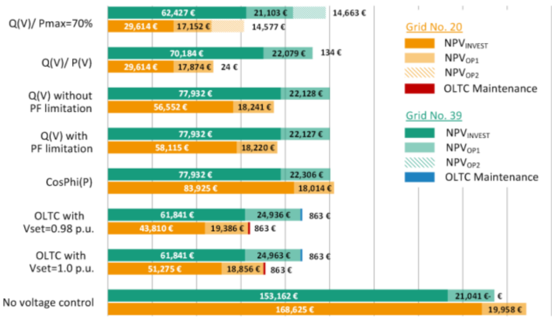

Fig. 5: Total net present value (NPV) of investigated local voltage control strategies referred to the beginning of year t_1. NPV_{Invest}: Grid reinforcement, NPV_{OP1}: Network losses + maintenance, NPV_{OP2}: Reduced PV feed-in. [6]

3.5 RECOMMENDATIONS FOR THE TRANSITION FROM UNI- TO BI-DIRECTIONAL DISTRIBUTION GRIDS

For the transition from stage one to stage two as well as for an early preparation for stage three the following recommendations can be given based on the experience gained in the Task 14 member countries:

- If high nationwide PV penetration scenarios are expected, it is important adapt network codes and laws in time to pave the way for an active PV contribution on power system operation (preparation for stage 3). This includes:
    - Adequate settings of Over-/Under-Voltage and frequency protection shall make sure that the PV systems remain connected to the grid and feed-in power during under-frequency situations and do not disconnect immediately during an over-frequency event.
    - Readiness of frequency support mechanisms provided by PV inverters (e.g., implementation of local P(f) droop characteristics) should be available.
    - PV systems should be equipped with remote control interfaces from an early penetration stage on. Otherwise, high costs for retrofitting existing PV systems might occur at a later stage.
- If autonomous reactive power capabilities of smart PV inverters are to be used to increase the hosting capacity of distribution grids, the following advices should be taken into consideration:
    - High PV deployment can happen quickly. It is therefore important to make a decision about the usage of reactive power by PV at an early penetration stage. Otherwise, there is a significant risk of having many PV systems without reactive power capability connected to the grid.
    - There are many different solutions available: DSOs should opt for control strategies that provide reactive power in a technically efficient manner (Q only if technically required). This means Volt/VAr control rather than fixed reactive power provision or fixed power factors.
    - In order to reduce costs for grid reinforcement and/or grid augmentation, the reactive power capabilities of PV need to be considered already at the grid planning stage.
- Temporal active power reduction can help to delay or avoid grid reinforcements and/or grid augmentations. Feed-in compensation approaches should be prepared in parallel.
- Novel DSO assets and revised grid planning principles can help to increase the hosting capacity of distribution grids. However, current regulations in the context of yardstick competition mechanisms might hamper the applicability of such solutions. Hence, the regulatory framework should be checked for hidden barriers.

Figure 6 shows the necessary role of PV for different penetration level.

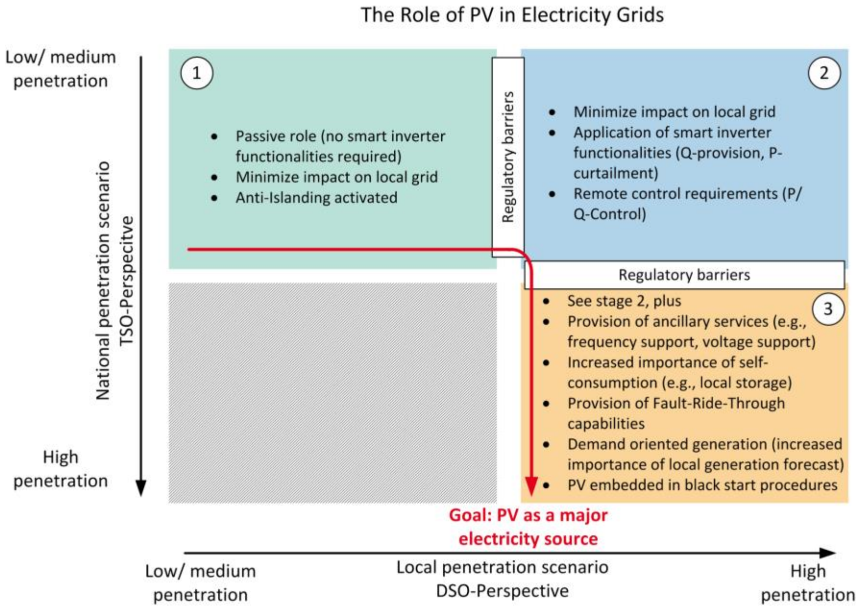

Fig. 6: The role of PV in electricity grids depending on the local and national penetration level.

4 FUTURE PROSPECTS FOR THE TRANSITION TOWARDS HIGH PENETRATION SCENARIOS

As of today, most of the IEA Task 14 countries have already entered stage 2, where high level PV penetration is a reality for a certain number of distribution grids. As more distribution systems are changing from consumption to supply grids, high nationwide penetration scenarios arise (stage 3). In consequence new challenges for a stable operation of the overall power system arise. Traditional collaboration strategies between transmission and distribution systems operators and their role in the overall power system operation have to be reconsidered. This transition process will open new opportunities for existing and newly installed PV systems to actively participate in the power system operation and hence to prove their suitability as a major electricity source in future power systems.

Aligning PV Generation and Electricity Demand

A key element for a more demand driven PV generation is to move from static feed-in-tariff systems, where pure active power feed-in is incentivized, towards more demand oriented systems.

The first stage of demand oriented PV generation has to take place on a local level, where locally generated PV energy is used to cover domestic loads. In this context, storage systems or manageable loads controlled by sophisticated energy management systems can be used to ensure customers' interest in increasing the PV self-consumption (compare section 3.2).

On a second stage, the same local energy management system could be embedded within a central management system to receive signals or set values (prices or activation). The local energy management system can then decide whether the locally generated PV energy shall be used to cover domestic loads or if the energy gains higher yields, if sold to the market or a system operator via a virtual power plant.

For a successful application reliable local PV and load forecasting systems are essential to determine the available amount of energy on a day-ahead and intraday basis.

Provision of Ancillary Services

The reduction of conventional fossil-fuelled generation capacity is a logical and intended consequence on the way towards decarbonized electric power systems relying mainly on RES electricity. It also means that alternatives for providing ancillary services to TSOs whilst considering the DSOs/TSOs requirements must be found. A strong focus of future R&D is expected to be set on the provision of ancillary services to TSOs by PV systems, in particular:

- Frequency control (primary, secondary, tertiary and instantaneous control)
- Voltage support (static/ dynamic)
- Grid operation (congestion management, capacity scheduling, reserve capacity)
- Black start and system restoration

Interaction of Smart Grid, Smart Inverters and Smart Markets

From the perspective of a PV system operator, simultaneously fulfilling the requirements of smart markets and smart grids can sometimes be contradictorily. Hence, standardized procedures are required which regulate the responsibilities of smart grids and smart markets in future electric power systems. One possible step towards finding solutions is e.g. the BDEW Roadmap for the transition towards smart grids in Germany [27].

For the time being, a successful provision of most of the above mentioned ancillary services (smart grid) and market operations require a combination of reliable forecasting systems, standardized ICT backbones and higher-level intelligence, implemented and operated also at the distribution system level. Defining proper standards for technical solutions and role models (including business models) for the above mentioned issues will be a key factor for a successful transition towards secure and reliable high national PV penetration scenarios.

5 OUTLOOK

The IEA-PVPS Task 14 will continue its work on identifying technically effective and economically efficient solutions for high PV penetration scenarios in electricity grids. The scope of Task 14 was further extended to include "market implications with high PV penetration" and "communication and control" subtasks. In the current working period (2014 – 2018) IEA-PVPS Task 14 therefore consists of the following subtasks:

- **Cross-Cutting Subtask:** Market implications with High PV Penetration
- **Subtask 1:** Energy Management with High PV Penetration
- **Subtask 2:** High Penetration PV in Local Distribution Grids
- **Subtask 3**: High Penetration Solutions for Central PV Generation Scenarios
- **Subtask 4:** Smart Power Converters for High Penetration PV and Smart Grids
- **Subtask 5:** Communication and Control for High Penetration of PV

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The authors are solely responsible for the content of this paper.

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