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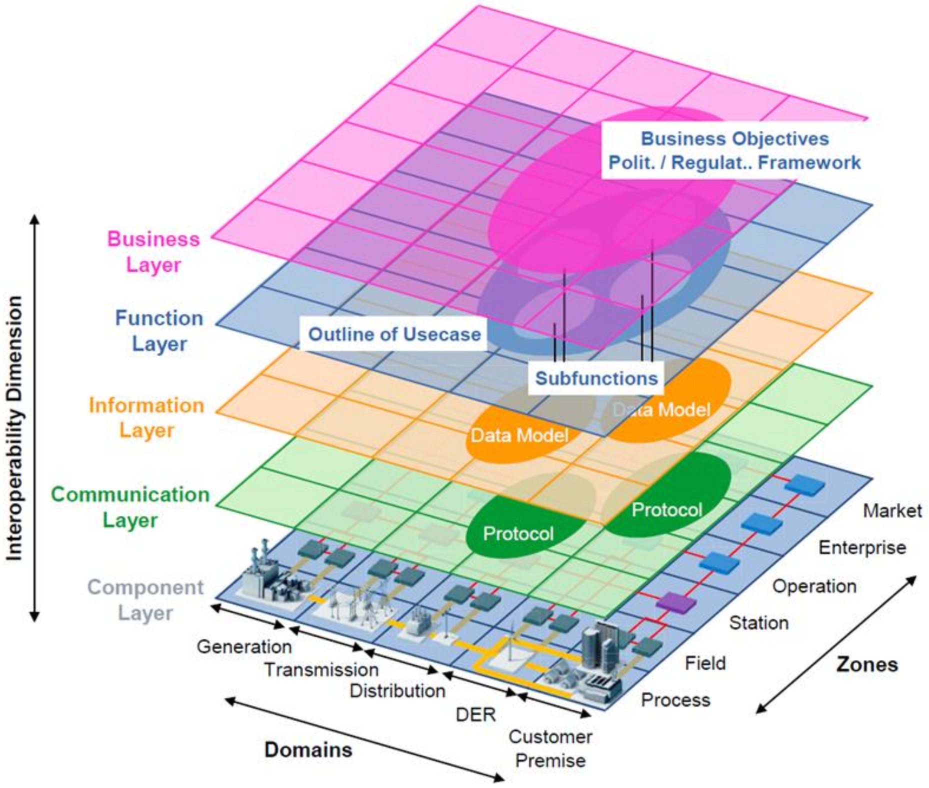

Task 14 Solar PV in the 100% RES Power System

PVPS

Communication and Control for High PV Penetration under Smart Grid Environment

Overview on Control Strategies and Communications Technologies

Report IEA-PVPS T14-12:2020

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The IEA carries out a comprehensive programme of energy cooperation among its 32 members and with the participation of the European Commission. The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the collaborative research and development agreements (technology collaboration programmes) within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems."

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the collaborative research and development agreements (technology collaboration programmes) within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas. This report has been prepared under Task 1, which deals with market and industry analysis, strategic research and facilitates the exchange and dissemination of information arising from the overall IEA PVPS Programme.

The participating countries are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association and the Copper Alliance are also members.

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What is IEA PVPS Task 14?

The main goal for the third phase of Task 14 will be "to prepare the technical base for Solar PV as major supply in a 100% RES based electric power system". To reach this goal, Task 14 will continue its work in order to develop solutions and reduce technical barriers to enable PV to become the main source of power in a future 100% RES power system. In summary, the following key challenges were identified which will be addressed in the work programme for the third phase:

- With growing PV (and other RES) capacity in transmission systems and ancillary services delivered upstream from distribution to transmission, a more integrated viewpoint on PV integration is needed.
- New approaches to the management of power systems with declining inertia need to be developed to ensure system stability
- Operational and long-term planning with large amount of PV (and other RES) remains a key challenge in the future 100% RES scenario
- Value/Cost, market design and operation aspects is highly relevant to bring cost reductions on the component side to the market
- Reliability, resilience and PV in micro grids are increasingly "hot topics" to be addressed
- Solutions for expanding power systems in emerging countries are urgently needed, as Solar PV can be the most cost-effective solution on the supply side.
- With Smart Grids becoming reality and opening new opportunities, the possible role of PV in a future Smart Grid needs to be discussed.
- Considering insular power systems as the most challenging for the future 100% RES scenario, the discussion about how to design the specific role of PV in these systems is needed.

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Energie, Mobilität,
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IEA Forschungskooperation
im Rahmen von open4innovation

FFG
Promoting Innovation.

LIST OF ABBREVIATIONS

IEA	International Energy Agency
CLS	Controllable Local System
SMGW	Smart Meter Gateway
DER	Distributed Energy Resources
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
FIT	Feed in Tariff
HV	High Voltage
LV	Low Voltage
MV	Medium Voltage
PCC	Point of Common Coupling
PV	Photovoltaic
RES	Renewable Energy Source
TSO	Transmission System Operator

EXECUTIVE SUMMARY

Currently the integration of PV systems in the distributed systems follows a “fit and forget” rule. However, with the increasing penetration level, the intermittent and fluctuating energy availability of PV systems are introducing many challenges to existing grids. For example, with the household and industries having own generations, their electricity consumption is no longer predictable by utilities. Therefore, gathering information about the PV system and even controlling the PV systems is of highest importance to utilities. The smart grid, the next-generation of power grid, is designed to enable the massive deployment and efficient use of distributed energy resources, including PV. To support real-time information collection, analysis, as well as automated control, the deployment of two-way communication and auto-control system for PV system integration is critical.

The IEA PVPS Task 14 Subtask C “PV in Smart Grids” will explore the communication and control for high penetration PV systems. The main intention is to survey the appropriate control strategies and communication technologies to integrate a high number of distributed PV systems into a smart electricity network. This Report summarizes the survey on the existing PV communication and control practice among Task 14 participating countries as well as reviews the literature of the state-of-the-art concepts for integration PV system under smart grid environment.

Section 1 starts with a definition of the terminology, and Section 2 gives an architecture overview of the control and communication requirements for PV integration to smart grid environment. Section 3 reviews the communication requirements and technologies. Section 4 explores the various concepts of integrating a high number of distributed PV. Section 5 presents the survey results about the current communication and control practice of PV integration. The reports ends with conclusions and explains the next steps of IEA PVPS Task14 Subtask C “PV in Smart Grids”.

1. DEFINITION OF TERMINOLOGIES

1.1 Smart Grid

The European Union has defined a smart grid as “an electricity network that can efficiently integrate the behavior and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety” [1].

The American National Institute of Standards and Technology (NIST) has another definition of a smart grid, as follows [2]: a modernization of the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements from the central and distributed generator through the high-voltage transmission network and the distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances and other household devices. A smart grid enables bidirectional flows of energy and two-way communication. Moreover, control capabilities will enable an array of new functionalities and applications.

Although there is no unique definition of the smart grid, in general, every smart grid definition comprises technical aspects and domains as well as actors. As the definitions show, one key element of the smart grid transition is the integration of new technologies from the Information and Communication Technology (ICT) domain with the existing grown infrastructure of automation and power distribution and transmission.

Smart grids can play a crucial role in facilitating the smooth integration of high shares of variable renewables and supporting distributed generation. In term of renewable energy, such as PV integration, smart grids can provide the following advanced technologies and applications to manage continuous balancing of the system [3]:

1) Better forecasting: Widespread instrumentation and advanced computer models allow system operators to better predict and manage PV variability and uncertainty.
2) Smart inverters: Inverters and other power electronics can provide control to system operators, as well as to automatically provide some level of grid support.
3) Demand response: Smart meters, coupled with intelligent appliances and even industrial scale loads, can allow demand-side contributions to balancing.
4) Integrated energy storage: Storage can help to smooth short-term variations in RE output, as well as to manage mismatches in supply and demand.
5) Real-time system awareness and management: Instrumentation and control equipment across transmission and distributions networks allows system operators to have real-time awareness of system conditions, and increasingly, the ability to actively manage grid behavior.

1.2 Smart Meter

A smart meter is an advanced energy meter that obtains information from the end users’ load devices and measures the energy consumption of the consumers and then provides added information to the utility company and/or system operator for better monitoring and billing. With a smart meter, electrical data such as voltage and frequency are measured and real-time energy consumption information is recorded. Smart meters support bidirectional communications between the meter itself and the central system. Also, a smart meter can have the built-in ability to disconnect-reconnect certain loads remotely and can be used to monitor and control the users’ devices and appliances to manage demands and loads within the “smart-buildings” in the future [4]-[5].

The typical functions of smart meter are [4]: 1) two-way communication; 2) data collection; 3) data recording; 4) data storing; 5) load control; 6) programming function; 7) security function; 8) display function; 9) billing function.

1.3 Smart Metering System

The term smart metering system is different from smart meters. A smart meter is a device that measures and possibly stores the consumption of a commodity. The term smart metering system is referred to the infrastructure which includes smart meters, communication networks and infrastructure between the smart meters and the remote entities, such as the energy consumer, the meter operator, the supplier of energy or the utility and the meter data management systems [6].

1.4 Smart Meter Gateway

The core of the smart metering system is called Smart Meter Gateway (SMGW). It acts as a central communication unit between three different network types: the wide area network (WAN), the home area network (HAN) and the local metrological network (LMN). Both HAN and LMN belong to the consumer’s local area network (LAN). The gateway not only serves as a communication and control unit between the meters and the utility, but is also responsible to ensure the privacy of the customer data. The smart meter gateway is responsible for the secure storage and forwarding of data collected by smart meters and other smart devices installed in a house or a premises. The gateway periodically communicates with the utility servers via WAN. In other words, the SMGW acts as a translator to ensure the data collected from the LAN is properly communicated to the WAN for the individual device. With several smart meter gateways installed, the WAN receives an abundance of information so the smart meter gateway is programmed to ensure the data being communicated from smart meter A, is logged as smart meter A for devices in the WAN.The gateway also gets instructions from the load distribution controller based on the load in the smart grid [6]-[7], [70]-[72].

1.5 CLS-Infrastructure

The technical system to integrate so called controllable local systems (CLS) like PV-Systems, battery storage or other DER into a smart metering system is called CLS-Infrastructure. The CLS-Infrastructure could be part or an addition of the smart metering system that is already in place. If a local DER is remote controllable then it is a CLS. Typically a CLS-Infrastructure realizes that intelligent control functions by usage of a so-called CLS control box and a CLS management system. The CLS control box is suitable for converting the protocols and data models of the smart metering system to the protocols and data models of the specific DER. It is also possible that the DER includes that functionality directly into their own system. Always necessary is a CLS management system for controlling a maintaining the CLS-Infrastructure, such a system is called CLS-Management or CLS-Backend [68].

1.6 IEC 61850

The IEC 61850 is a communication standard and data model that provides uniform and standardized communication and control of substations. Nowadays it is the established communication standard on the worldwide market for the automation of substations [45]. Since several years the utilization of IEC61850 has been extended to wind power, hydro power and decentralized power systems (DER).

1.7 Common Information Model (CIM)

The Common Information Model (IEC 61970) is a semantic model which explains the single components of a distributed energy system. IEC 61968 extends this model to cover other aspects of power system software data exchange [45]. The European TSOs organized within ENTSO-E defined a specific CIM profile (CGMES) which supports the exchange of network model data among each other.

1.8 SunsSpec

SunSpec is a communication standard for solar inverters sponsored by the U.S. Department of Energy and is now maintained by the industrial consortium “SunSpec Alliance”. With this standard, it is possible to read the settings and measured values of SunSpec-capable PV inverters from different manufacturers and to control the output of an inverter and change settings. It has a modular structure to support different device patterns and utilizes the widely adapted modbus industry standard.

1.9 Smart Grid Information Model (SGAM)

The methodology for standardization, documentation and presentation of smart grid architectures or functions. It was developed under the EU commission mandate M390 and the mandate of the US Department of Commerce by the Nation Institute of Standards and Technology (NIST). The complete energy system is divided in different zones and domains, for example distribution, transmission, DER and customer premises and starting from process to market zones. The proposed systems are discussed in five different layers which allow to discuss separately the components, the communication (protocols), the data information model, the functions and the business context (this methodology is used and further explained in chapter 3.).

1.10 Distributed Energy Resources (DER)

Distributed Energy Resources (DER) are sources of energy which, unlike conventional power plants, wind parks or large ground mounted photovoltaic plants, generate little energy but contribute to the stable energy supply through aggregation. These can be small plants for renewable energies such as photovoltaic, geothermal or biogas plants. One speaks in this context also of Distributed Generation (DG). These small-scale systems must be integrated into the smart grid or microgrid at the low and medium voltage level of the electricity network.

2. HIERARCHICAL ARCHITECTURE OF DISTRIBUTED ENERGY RESOURCES (DERS) INCLUDING PVS UNDER SMART GRID ENVIRONMENT

2.1 The Smart Grid Architecture Model (SGAM) Framework

The smart grid can serve the diverse needs of many stakeholders, such as utilities, millions of industrial, business and residential customers, solution providers and different regulatory environments. Those systems should work together not just across technical domains but also across enterprises which are not part of the existing utility industry. The SGAM framework sets up a holistic architecture template of smart grids to achieve interoperability in such a massively scaled, distributed system. Figure 1 shows an SGAM Framework developed by CEN-CENELEC-ETSI Smart Grid Coordination Group [8], which is based on the existing work approaches in [9]-[12].

The SGAM model divides the components of the power system into domains and zones, see Figure 1. The domains are arranged according to the electrical energy conversion chain. The SGAM zones represent the hierarchical levels of power system information management. The fiver layers represent the interoperability categories in the context of smart grids. The intention of this model is to represent on which zones of information management interactions between domains take place.

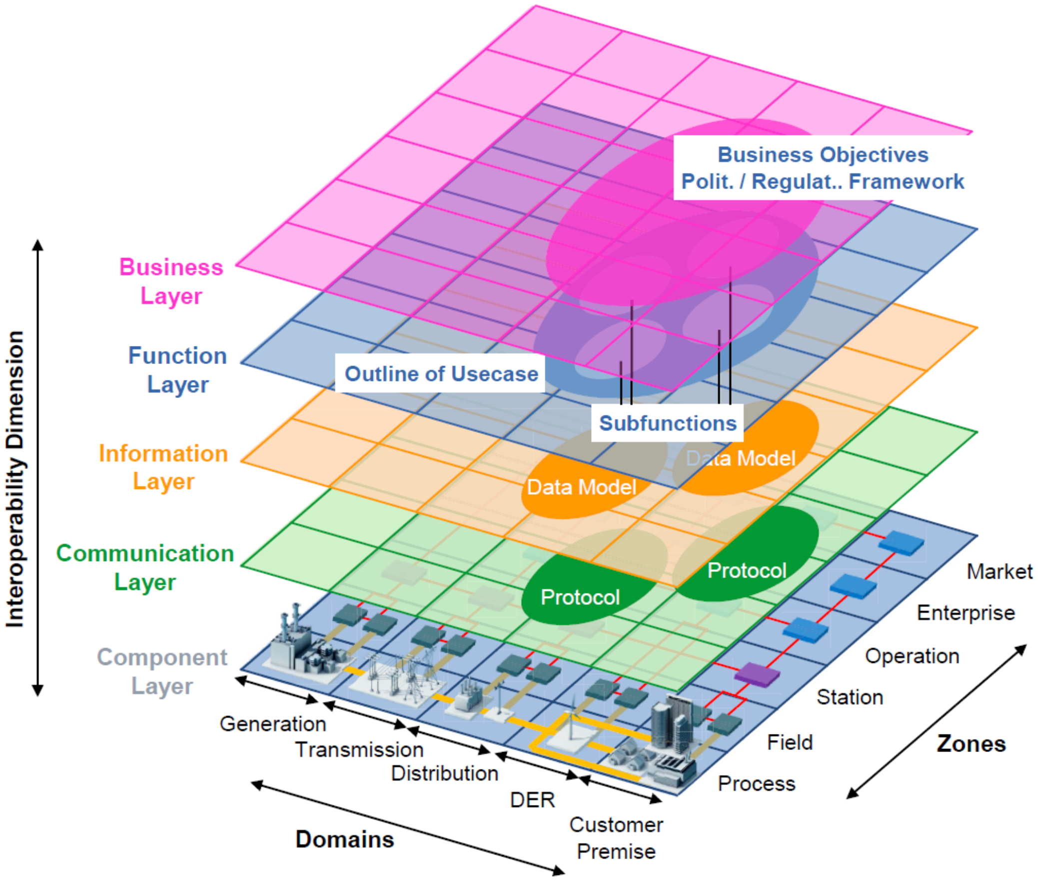


Figure 1: SGAM Framework [8]

2.2 DER Architecture Using SGAM Methodology

With millions of DER systems widely dispersed over the grid, it might be not feasible for utilities to have direct control on DERs in an unstructured way due to complexity. So a hierarchical approach is necessary for utilities to interact with these DER systems. Figure 2 [11] shows the five-level hierarchical DER system architecture mapping to the SGAM framework. The DER system management spans the process, field, station, operation zones and the distribution and customer premises domains. Interactions also exist to enterprise and market zones and, potentially, to the transmission domain.

A brief explanation of the five-level hierarchical control of the DER system is given below.

Level 1 DER Systems: The lowest level and includes the actual cyber physical DER systems themselves. These DER systems will be interconnected to the local grid at electrical connection points (ECPs) and to the utility grid through the point of connection (POC). These DER systems will usually be operated autonomously based on local conditions through pre-set software values at deployment. These values may be modified locally by DER owners. A common protocol used at this level is ModBus. When interacting with higher levels, mapping of ModBus to the IEC 61850 data models should be used.

Level 2 Facility DER Management: the next higher level in which a facility DER management system (FDEMS) manages the operation of the Level 1 DER systems. For simple facilities, such as residential home, the FDEMS may be combined with the DER controllers, basically providing communications capabilities to level a DER systems. Larger FDEMS will be managing multiple DER systems in commercial and industrial sites, such as universities and shopping malls. A number of different protocols could be used such as SEP2, BACnet, or OPC/UA but the protocols should be mapped to the IEC 61850 data models.

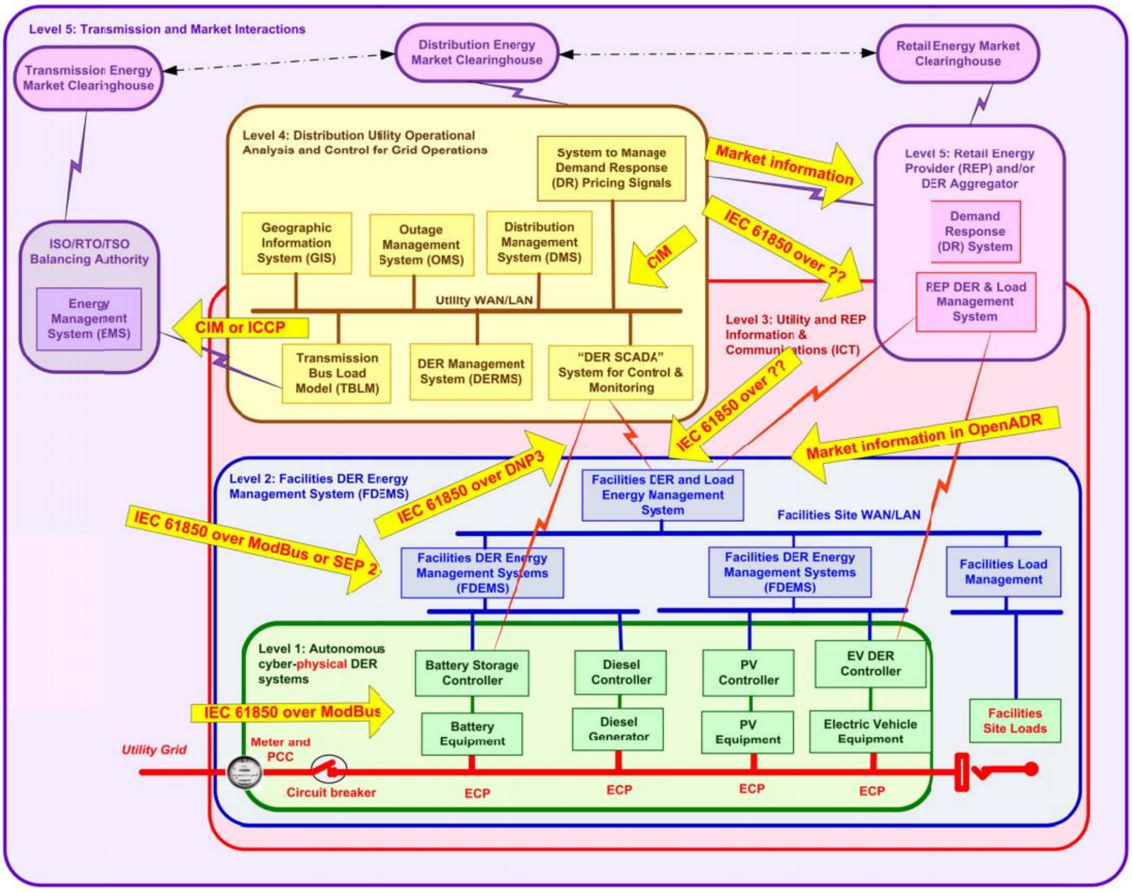


Figure 2: Mapping of the Distributed Energy Resource (DER) including PV to the SGAM framework [11]

Level 3 Information and Communications Technology (ICT) Infrastructure: It provides the information exchanges beyond the local site to allow utilities and market-based aggregators and retail energy providers (REP) to request or even command DER systems to take specific actions, such as turning on/off, setting or limiting output, and providing ancillary services. The combination of this level and level 2 may have various scenarios. Power system management interactions should be based on IEC 61850 with mapping to DNP3, SEP2 or XMPP, while financial interactions could use other data models and protocols, such as OpenADR.

Level 4 Distribution Utility Operational Analysis: Applies to utility applications that are needed to determine what requests or commands should be issued to which DER systems. Utilities monitor the power system and access if efficiency or reliability of the system can be improved by having DER systems modify their operation. Once the utility has determined that modified requests or commands should be issued out, it will send these out as per level 3. The interactions within the utility are expected to use the Common Information Model (CIM) (IEC 61968 and IEC 61970), MultiSpeak, or similar data models over "Internet XML-based protocols" such as SOAP, XMPP, OPC/UA, etc.

Level 5 Transmission and Market Operations: Represents the highest level, and involves the larger utility environment where regional transmission operators (RTOs) or independent system operators (ISOs) may need information about DER capabilities or operations and/or may provide efficiency or reliability requests to the utility. This may also involve the bulk power market systems, as well as market functions of retail energy providers.

The architecture diagram shows that a number of different communication technologies may be used in different environments for different purposes. More than one type of communication media may be used across a network. Different protocols may be involved and different types of information exchanges may be needed. Cybersecurity needs to be "end-to-end", but different media and protocols use different cybersecurity methods. IEC61850-7-420 and IEC61850-90-7 are standards that define the data models for most of DER functions. These cover the "power system management" interactions. "Financial" interactions which, include pricing signals, are described by other data models, such as OpenADR. There is a variety of publications that discus smart grid communication architectures, technical solutions and standardization [13]-[24].

2.3 Communication Architecture for DER Integration

Figure 3 shows a standard layout for smart grid communication architecture [25].

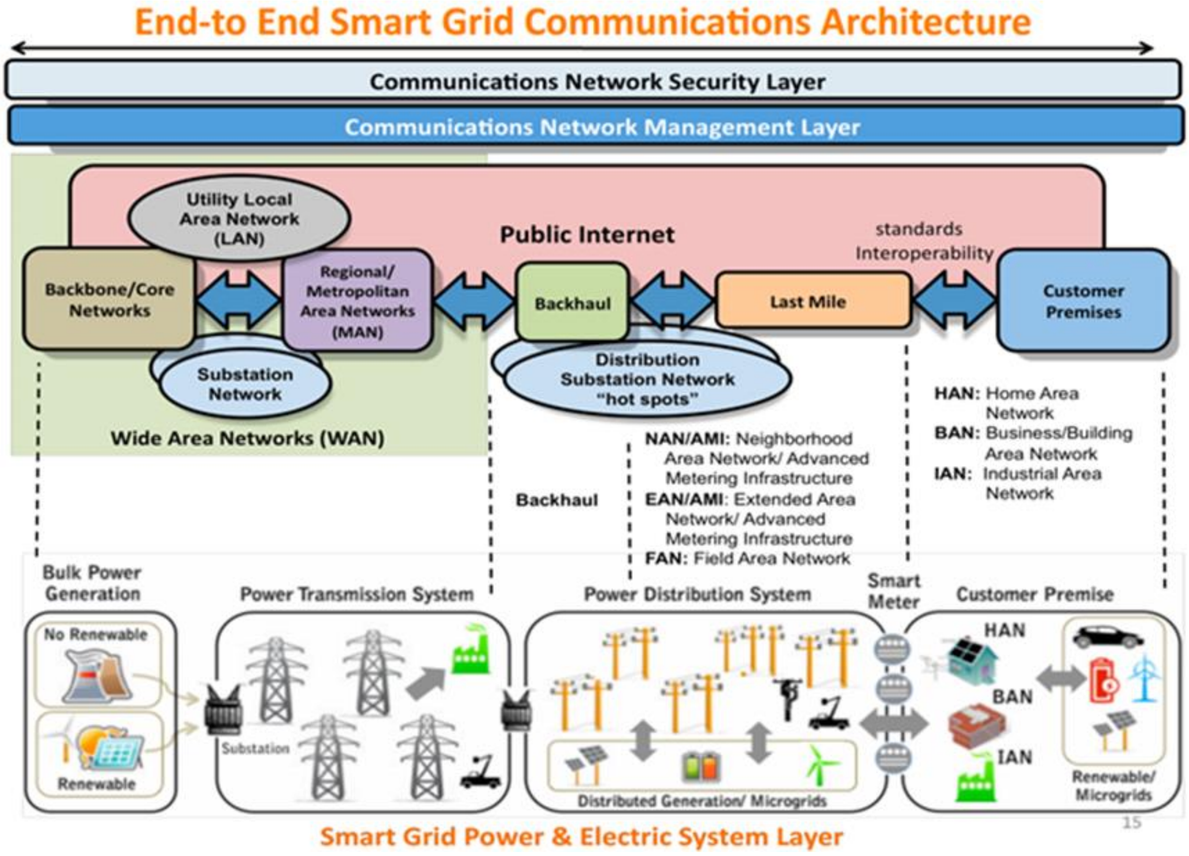


Figure 3: Smart grid communication architecture [25]

It gives a high-level overview on how two-way communication is achieved for solar PV integration. The communication network enabling the full functionality of solar inverters consists of a hierarchical architecture: (1)

The Home Area Network (HAN) is a communication network of home appliances, smart or ordinary devices, small scale PV or wind, and Home Energy Management (HEM) within a home that can be connected to each other by wireless communications such as ZigBee, WiFi or radio frequency. A similar concept includes Building Area Networks (BAN) and Industrial Area Networks (IAN). (2) The neighbourhood area network (NAN) and Field Area Networks (FAN) comprise a number of HANs where meter data from different HANs are delivered to data concentrators. The communication of NAN can either be wireless or wired depending on size of network, data amount, location and others; (3) The backhaul is the intermedia link between NANs and utility’s wide area network (WAN); (4) WANs form the high-bandwidth communication backbone used by the transmission and the bulk generation systems. A WAN aggregates data from multiple NANs and conveys it to utility company’s private networks.

3. COMMUNICATION TECHNOLOGIES AND PROTOCOLS FOR INTEGRATING DISTRIBUTED PVS

The design of communication system for distributed PV systems is influenced by many factors, such as: (1) type and configuration of the equipment. Different devices require different time of response; (2) physical locations can determine the type of connection, data traffic volume and maintenance costs; (3) Control system, which can be centralized or decentralized, directly affects the communication architecture.

A list of key considerations for choosing suitable communication technologies for solar PV installations are given below [26]:

- **Data rate:** The amount of information that is successfully transmitted through a network.
- **Latency:** The period between the moment a message is generated until it is processed in the destination device. Most power system control and protection functions have tight delay constraints. Latency depends on many factors, such as data bandwidth, message size and processing in intervening equipment.
- **Reliability:** Reliability includes “reliability, availability and maintainability of the communication system”. It accounts for software and hardware malfunctions, downtime due to maintenance and network reconfiguration time.
- **Security:** The ability of a network to protect against unauthorized intrusion. Physical security is achieved by limiting the access to physical communication infrastructure. Cybersecurity requires careful choices of technologies throughout the communication network, such as encryption, firewalls, password management and antivirus.
- **Interoperability:** The ability of one or more devices to exchange information without special effort. It is achieved by using standard data model, protocols and methods of data transfer.
- **Scalability:** The ability of a communication system to handle an increasing amount of devices and users.

3.1 Communication Technologies

Different network technologies are used in different layers of smart grid communication networks. Distributed solar PV systems generally are connected to HAN and NAN/FAN network, which is the so-called “last-mile” communication network. The following sections give an overview of existing and widespread communication technologies used for distributed solar PV system integration.

3.1.1 Wired technologies

Power Line communication (PLC): PLC uses electrical power lines as signal carriers. This is allows utility companies to use single infrastructure for both power and data transmission. The main application of PLC technologies is the last mile communication. The disadvantages of PLC technologies are: (1) lack of protection to noises from other power signals; (2) connection interrupts when there is an open circuit; (3) Physical topology of the grid, impedance fluctuations and wave reflection at the terminal point cause high signal attenuation and distortion; (4) Lack of protection to unauthorised access.

Ripple control: Most distribution system operators (DSO) use ripple control systems to control specific loads, such as water heaters, washing machines, electrical heating systems or public lighting. With only minor modifications a ripple control system can be used to control photovoltaic (PV) power plants and thus to increase the PV hosting capacity of an electrical power system.

Digital Subscriber Lines (DSL): DSL refers to a suite of communication technologies that enable digital data transmissions over telephone lines. The main advantage of DSL technologies is that electric utilities can interconnect residential users to control centers avoiding the additional cost of deploying their own communication infrastructure. The technology is mostly applied in all type of HAN, IAN and FAN. The disadvantages are cable breakage and water ingress difficulties in failure pinpointing.

Optic Fiber: optical communication technologies have been widely used by electric utilities to build the communication backbone interconnecting substations with control centers. The major advantages of this communication technology are: (a) able to transmit data packets over several kilometres with a total bandwidth of tens of Gbps; (b) its robustness against electromagnetic and radio interference, making it suitable for high-voltage environments. One main constraint of optical communication is its very high cost for implementation

3.1.2 Wireless communication

ZigBee: This technology is based on IEEE 802.15.4 standard. It can provide short-range (up to 100 meters and up to 1.600 meters with ZigBee Pro) low-rate wireless communication for personal area networks. It supports different network topologies and applies for residential, commercial and industrial buildings automation, energy monitoring and AMR systems. The advantage of ZigBee is the low implementation cost and power consumption as well as the high level of security. However the slow data rates, limited area coverage and the interference by parallel wireless networks (such as Wi-Fi) restrict deployment of ZigBee technology to in-home applications.

Wi-Fi: based on IEEE 802.11 series of standards. It provides data rates from 2 to 600 Mbps and operates on ISM frequency bands, such as 2.4 GHZ, 3.6 GHz and 5 GHz. Wi-Fi gives advantages in fast, secure and reliable connection, but short operation range (up to 100 meters), high cost for deployment and high power consumption constrain the implementation of WLAN technology to primarily residential and commercial local networks.

WiMAX: Based on IEEE 802.16 standard. It can support long-distance (up to 7–10 km) broadband (up to 100 Mbps) wireless communications, especially in rural and suburban areas. This technology uses dynamic routing. In the case of outage of one node, all others are capable to communicate through the rest of the points because of interconnected structure of the network. The benefits of this technology include high coverage, robustness and self-healing, wireless mesh. Its main application is found in home automation and AMR systems. The technology has limitations in low-speed data rates and vulnerability to the interference from other wireless networks.

3G/4G cellular network: Public cellular networks which has a major benefit of larger coverage area. Utilities have extensively used cellular technologies, such as GSM, GPRS and EDGE, for data communications in SCADA and AMR systems. A shortcoming of cellular data services is that they are relatively expensive. Cellular networks are experiencing a rapid evolution and new generations of technologies supporting higher data rates as well as more sophisticated data communication services.

Satellite: The satellite communication is used for remote monitoring and control of electric substations and especially for the time synchronization based on global positioning system (GPS) technology. The advantages of technology are global coverage and fast installation. The constraints are long round-trip delays, dependency on weather conditions and high initial cost.

LoRaWAN: LoRaWAN is a media access control layer protocol for managing communication between LPWAN gateways and end-node devices, maintained by the LoRa Alliance. Version 1.0 of the LoRaWAN specification was released in June 2015. [53]

IEEE 2030.5-2018 - Smart Energy Profile Application Protocol: This Standard defines an application profile which provides an interface between the smart grid and users. It enables management of the end user energy environment, including demand response, load control, price communication, distributed generation, energy storage, and electric vehicles as well as the support of additional commodities including water, natural gas, and steam. This standard defines the mechanisms for exchanging application messages, the exact messages exchanged including error messages, and the security features used to protect the application messages.

3.2 Communication Protocols

Communicating systems use well-defined formats (protocol) for exchanging various messages. The communication system arranges the information exchange between different grid members, such as substations equipment, DERs and control centers through the common frame of regulations for data format and transmission. Different grid applications have different constrains in terms of necessary communication, which is resulted in various communication protocols existing for data exchange in power industry.

Internet protocol suite (IPS): IPS is a set of protocols to provide Internet services. The following are mostly used in power system applications: Network Timing Protocol (NTP) for time synchronization, Internet Protocol (IP), Transmission Control Protocol (TCP), User Datagram Protocol (UDP), File Transfer Protocol (FTP) and Simple Mail

Transfer Protocol (SMTP). The protocols that supply transport and network services, such as TCP, UDP and IP, are of the highest importance. IPS is used for carrying such specific automation protocols as Modbus, DNP3 and IEC 61850 over a network environment by conveniently utilizing Ethernet data link. These protocols are encapsulated in the TCP/IP stack and act over its layers. This practice gives advantages in better utilization of the dedicated protocols for SG applications by modifying them specially for using with IPS as a standard for transmission over the network.

ModBus: Modbus is a serial communication protocol, which is commonly used for connecting industrial electronic devices. The protocol works at application level with a foundation on a client/server architecture, where the client requests server operations. By using a master multiplexing in gateway based networks for gathering diverse communication interfaces, Modbus is capable of routing different system configurations with more than one master controlling the slave devices. Modbus can be deployed over several communication interfaces, such as: TCP/IP over Ethernet, Serial Transmission and Modbus Plus.

DNP3: The Distributed Network Protocol version 3.3 (DNP3) is an open standard for telecommunication designed for interaction between master stations, RTUs and other intelligent electronic devices (IEDs) in electrical utilities and industrial environments. It was designed for SCADA systems to transmit considerably small data packets. DNP3 is typically deployed on serial communication (RS-232 and RS-485) over various physical links, such as twisted pair, optic fiber, radio and satellite communication. DNPS is more robust, efficient, and interoperable than Modbus, at the cost of higher complexity.

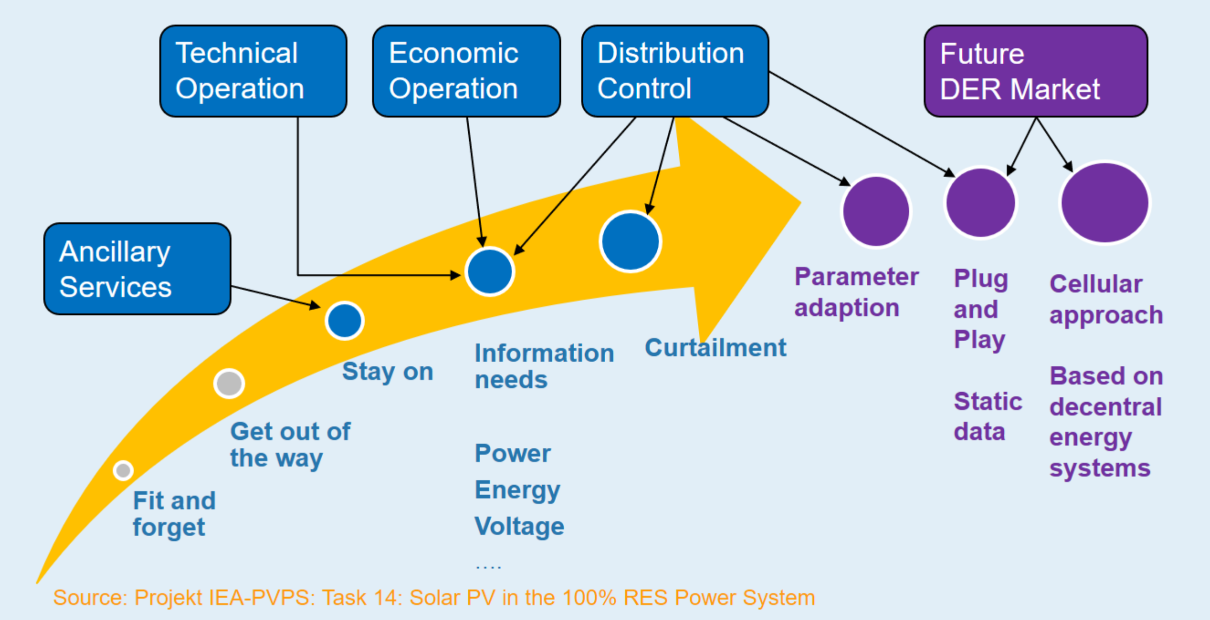
IEC61850: IEC 61850 is a set of standards of IEC Technical Committee 57 (TC57) for electrical substations automation systems. The main communication architecture concept in IEC 61850 is the creation of data objects and services independent of any particular protocol, or ‘abstracting’ them. This allows further mapping of the data objects and services to any other protocol meeting of the data/service requirements. IEC 61850 provides a variety of advantages, including interoperability of devices from different suppliers, lower installation, configuration and maintenance costs, enhanced scalability and possibility for further improvements of systems automation processes. It was originally developed for electrical substations LANs, so it mostly employs TCP/IP protocol and Ethernet link as a communication medium.

4. EXISTING CONCEPTS OF INTEGRATING DISTRIBUTED PVS

Section 4 summarizes the existing communication technologies and protocols. This section focus on the existing concepts for integrating and coordinating the operations of the distributed solar PV systems.

Currently, most PV systems are connected to the grid usually with a “fit and forget” principle. PV systems operate autonomously through the advanced solar inverter functions. However with the increasing penetration level, a lot of technical challenges, such as managing the PV intermittency and variability, economic, regulatory challenges are emerging. Also the autonomous inverter actions could increase grid instability under certain grid conditions. To deal with the intermittent nature of an increasing share solar PV and the increasing electricity demand, the future electrical power system will need to become more intelligent, which requires communications capability in solar PV systems as an essential functionality.

The advent of smart grid will not be through a revolution - this is only possible through a gradual evolutionary change of the electrical network [27]-[29]. Microgrids and virtual power plants (VPPs) are two promising approaches to high penetration of solar PV systems integration in the distributed system under current the infrastructure. Both of these aggregation platforms are seen to be the building blockings for future smart grid solutions.



Source: Projekt IEA-PVPS: Task 14: Solar PV in the 100% RES Power System

Figure 4: Evolution of communication needs for PV integration into smart grids

4.1 Grid Codes

Grid Codes are the regulatory framework for the integration of DER into the electricity network. In many countries there are different grid code specifications depending on the voltage level. Grid codes describe the obligations a power system has to fulfil to connect to the network. The network ask for information on the actual power input of the generator, expects the delivery of ancillary services and needs measures to be able to curtail the power input of the generator.

4.1.1 Information from grid integrated DER

The information needed from the DER includes the generated energy measured with certified energy meters and the actual energy delivered to the grid.

Future scenarios with distributed energy systems have the demand for the knowledge of the actual network status also in the medium and low voltage level. The internal measurements within the DER are a potential low cost source for these kind of information like voltage or power factor.

4.1.2 Ancillary Services from DER

In contrast to many grid codes today which ask for disconnection of the DER in case of network problems (get out of the way strategy) modern grid codes in Europe, the US and Asia-require for ancillary services also from the DER, mainly frequency support, voltage support and balancing power.

4.1.3 Curtailment

Would you drive a car with a missing steering wheel? Similarly network operators who are responsible for the operation of the network and the quality of energy supply need a “steering wheel” for the interaction with millions of DER. Therefore, new grid codes increasingly include the directive for curtailment of DER in case of unbalancing between load and supply.

4.2 Microgrid

The definition of a microgrid by the U.S. Department of Energy is as follows [30]. A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. Microgrids can operate under grid-connected mode or island mode. In grid–connected mode, the microgrid operates as part of the utility grid. In island mode, the microgrid is disconnected from the utility grid and supplies only loads within the microgrid boundaries. An autonomous control system is expected to maintain frequency and voltage within predefined boundaries. In this way, the consumers may receive continuous service [31]-[35].

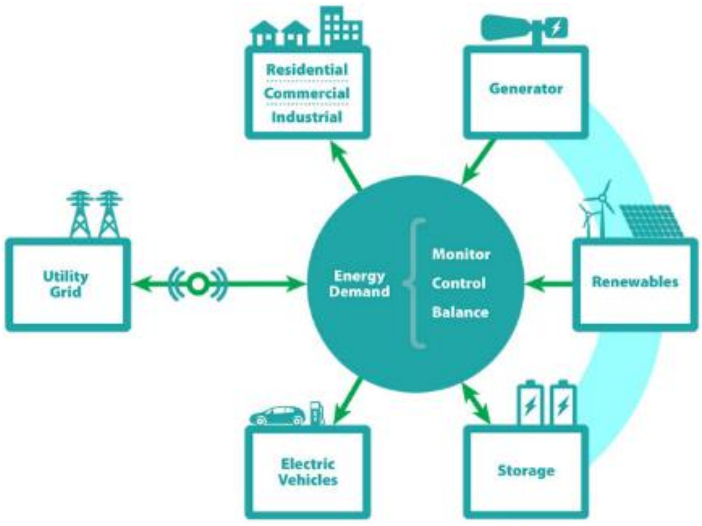


Figure 6: A high-level microgrid concept [36]

A typical microgrid includes various DERs, non-renewable distributed energy resources, energy storages, different types of loads, control and communication system, as shown in Figure 5. The control system is crucial for microgrids. It allows the microgrid to present itself to the bulk power system as a single controlled unit, have plug-and-play simplicity for each DERs, and meet the customers’ local needs.

There are 3 main communication /control architectures of microgrids: Centralized, decentralized and multi-layer (hierarchical) control [37].

In the centralized concept, the sources are controlled by a central master control system. The components inside microgrids are controlled through a local slave controller. Communication networks play an important role in centralized approaches. Fast and reliable communication with sufficiently large bandwidth is desirable for such systems. However, the reliability of a centralized approach is deteriorated in the event of failure of a central controller or its communication network.

In the decentralized concept, the individual sources share the load as per their individual capability and power control characteristics without any communication or limited communication with adjacent systems. Most of these systems follow the well-established droop control in the grid-connected and island mode of operation. However, real-time optimization of operating cost and source utilization under various operating conditions is not possible in this approach.

The hierarchical operation of the microgrids requires three control levels. The primary control deals with output power control of each individual DER unit and protection applications, which is based on local measurements. The secondary control deals with the economical and operational reliability of the microgrids. Tertiary control can be assumed as the inter action of multiple microgrids with a host grid. The dependence of control on communication network is significantly low, as compared with the centralized control, yet the communication plays a critical role in the overall optimization of the system operation. Although the hierarchical approach suffers from a loss of optimal performance during the failure of a communication link, microgrid operation continues at the suboptimal level with the help of local controllers.

In order to have operational control and protection system for microgrid, a sophisticated communication infrastructure is required to measure and manage loads, operate DERs. There are several communication protocols which exist in industry, such as Modbus, DNP3 and IEC 61850. The Modbus is a master/slave protocol which can be transmitted over different physical links such as RS232/485 and Ethernet. DNP3 is another master/slave protocol which mostly used in SCADA systems. IEC 61850 is a standard for communication in substation automation systems and is transmitted over Ethernet networks.

4.3 Virtual Power Plant (VPP)

Virtual power plants are based on a relatively new concept [38]-[41]. The main idea is based on a centralized control structure which connects, controls and manages a portfolio of DERs. VPPs provide opportunities to support the integration of DERs in the current power system by aggregating the various components and acting as a single player in the power system. VPPs rely upon software systems to remotely and automatically dispatch and optimize generation, demand side or storage resources in a single, secure web-connected system. Without any large-scale fundamental infrastructure upgrades, VPPs can stretch supplies from existing generators and utility demand reduction.

A VPP consists of three major components:

- Portfolio of DERs, including energy storage and dispatchable loads
- Information communication technology (ICT).
- VPP controller

In terms of structures and functionalities, VPPs can be seen as two complimentary entitles: Technical VPP (TVPP) and Commercial VPP (CVPP) [38]. DERs can simultaneously be part of both a CVPP and a TVPP. The TVPP consists of DER from the same geographic location. It is responsible for the correct operation of the DERs and energy storage systems, manages the energy flow inside VPP cluster and executes ancillary services. CVPP considers DERs as commercial entities, offering the price and amount of energy that can be delivered. This results into the optimization of economical utilization of VPP portfolio for the electricity market. The aggregated DER units are not necessarily constrained by location but can be distributed throughout different distribution and transmission grids.

In terms of control architecture, VPPs can be categorized in centralized VPP and decentralized (hierarchical) VPP. In centralized VPPs, the VPP dispatches the operating point of each DER. This requires that the VPP has accurate knowledge of the state of the DER. Decentralized VPPs on the other hand operate with a hierarchical architecture. In these VPPs, distributed local controllers are overplayed with either a central controller or with information exchange agents to form an integrated system.

VPPs and microgrids often are mentioned together as alternative solutions for integrating DERs. However important differences exist: Microgrids can operate in islanded mode while VPPs always are grid-tied. Other difference includes: Microgrid encompass a set of resources in a confined geography while VPP can mix and match among a diversity of resources over large geographic regions; microgrids typically only manipulate DERs at the distribution level, whereas VPPs can create a bridge to wholesale market. In this sense, VPP is software-based while a microgrid depends on hardware components [42]-[44].

5. EXISTING COMMUNICATION AND CONTROL PRACTICE FOR PV INTEGRATION: SURVEY RESULTS

This section presents the survey results conducted among Task 14 group members. The first round survey was conducted on early 2016 and a second round on early 2017. The survey focused on the smart grid projects where communication and control measures of distributed PV installations have been a significant part of the objectives and/or key learnings. Also the survey aimed to get an overview on the communication and control practices of distributed PV systems integration from the existing projects, existing legislations or standards, communication media, protocols, etc.

The current PV installed information in those countries is presented in Table 1.

Table 1: Summary of current PV situation in various countries based on the National Survey Reports of PV Power Applications of the year 2018 or 2017, depending on the availability on the website (https://iea-pvps.org/publications/).

Country	**Installed PV capacity (MWp)**	**Share of PV connected to HV (%)**	**Share of PV connected to MV (%)**	**Share of PV connected to LV (%)**	**Reference year**
Germany	42,400	6	35	59	2017
Denmark	990	Not available	Not available	Not available	2018
Japan	56,161	17	83		2018
USA	51,638	40	60		2017
Switzerland	2,173	0	5	95	2018
Austria	1,437	Not available	Not available	Not available	2018
China	44,260	Not available	Not available	Not available	2018

5.1 Existing and Planned Smart Grid Projects

A lot of smart grid projects with respect to the PV system have been planned or ongoing in recent years. A list of some major projects is given in Table 2.

In Greece, several universities and research centres participant in European co-funded projects. A smart grid demo project is also ongoing on the Island of Agios Efstratios. The project tries to achieve 85% RES contribution of the annual electricity demand. In Denmark, GREENCOM project aimed to balance the local exchange of energy at the community microgrid level. REStable project in Germany tries to identify the main technical, economic, and regulatory challenges on the way to operate the European power supply system mainly based on RES. Furthermore, the project C/sells analyses a cellular approach with a strong focus on smart grids. In Japan, a project regarding the “PV power generation control by two-way communication” started from 2015, other national level of projects are also planned for future. In the USA, over 100s of smart grid projects have been planned. The participants includes the government, research institutes, utilities and private companies.

Table 2: List of existing smart grid project with respect to PV systems

Country	Project name	Project details	Remark
Greece	IGREENGrid	The core of IGREENGrid is to share knowledge and promote the best practices identifying potential solutions for the effective integration of DERs in the six existing Demo Projects in LV and MV grids participating to the project and validating them via simulation in other environments to assess the scalability and replicability at EU level.	European co-funded project from FP7 and Horizon 2020
	DREAM	The project has laid the foundations for a novel heterarchical management approach of complex electrical power grids, providing new mechanisms for stable and cost effective integration of distributed renewable energy sources, as well as for enhanced consumer involvement in economic and ecological electricity use. Applying the principles of autonomous agent-based systems to the control and management of the electricity distribution grid allows the system to constantly adjust to current operational conditions and make it robust to exogenous disturbances. DREAM includes several layers of controls for normal, congested and post-contingency situations that uses different coordination strategies ranging from market based transactions to emergency demand response and create ad-hoc federations of agents that flexibly adjust their hierarchy to current needs.	
	INCREASE	Increase the penetration of renewable energy sources in the distribution grid by developing control strategies and ancillary services	
	national-level project	The national-level pilot project is intended to install smart meters to LV and AMI to MV customers among HEDNO network. It is foreseen to install about 200.000 residential and commercial meters in the next two years.	
	Green Island-Agios Efstratios	An R&D and demo ongoing project starting from 2013 with a total budget of EUR 8.9 million. The project is investigating the integration and operational control of variable renewable energy generation, mainly PV, wind and storage. The project tries to achieve at least 85% RES contribution of the annual electricity demand. The new power system will use the existing grid infrastructure incorporating RE, storage and monitoring, control and communication infrastructure to maintain power availability, quality, reliability, and safety requirements.	
	Smart Grids	A technical study deals with maximizing the penetration of renewables.	The study is financed by the

			EU “ELENA” programme
Denmark	GREENCOM	The project is to utilize the flexibility and intelligence in the low-voltage demand and local supply side infrastructure to create increased regulation capacity and reserve power in the centralized power grid. The project tries to balance the local exchange of energy at the community microgrid level, to avoid affecting the centralized grid with instability.	The project is financed by the Danish Energy Agency.
	DECODE	This project develops robust and cost-effective solutions to enhance the observability, controllability, protection and the interface between utilities, market players and prosumers in active distribution grids to support high renewable energy integration	The project is financed by the Danish Energy Agency.
Germany	REstable	The overall goal of the project is the identification of the main technical, economic, and regulatory challenges on the way to operate the European power supply system mainly based on RES and the elaboration of recommendations for their solutions. Project time is from 2016 to 2019. See Figure 6 for project diagram.	For further information, see: https://www.restable-project.eu/
	i-automate	Distribution of control characteristic in a smart grid with DER	
	SysDL 2.0	The SysDL 2.0 research project (ancillary services from area distribution grids) is focusing on developing and validating the system-based principles for the coordinated provision of ancillary-service upstream products. To this end, the project participants are incorporating the third-party operated generation systems available in the distribution grid. In addition, a field test is also being conducted in different distribution grids taking into regard the respective grid topology [50]. Communication Infrastructure SysDL 2.0 demonstrator: + TSO control center / DSO control center: TASE2 + DSO control center / DG remote control: IEC 60870-5 + DSO control center / SysDL demonstrator: CIM	
	CLS-APP BW Digitalisation of the Energiewende Made in BW.	This project will ultimately prove that intelligent measuring systems in combination with CLS control boxes are suitable for the operation of the Smart Grid, based on international standards. Existing components of the prosumer are integrated into the network in order to achieve improved feed-in management, adaptation and control of system services and secure market integration. These include, for example, PV systems, heating elements and cooling systems, as well as charging stations for electric cars and battery storage.	Funded by the state of Baden Württemberg, Germany.

		As part of the project, two existing CLS applications and 9 new CLS applications will be integrated into a CLS control box. At the Smart Grid Laboratory of the Ulm University of Applied Sciences these applications are tested for communication and functional properties. [68]	
	ESOSEG	The objective of ESOSEG is to promote the environmental compatibility, economic efficiency and resource efficiency of electricity grids and the security of electricity supply in Germany. Within ESOSEG an open source framework for simulation and optimization has been developed based on CIM standards.	Funded by the German Ministry of Economy and Energy.
	dena-Stakeholder-Prozess: Höhere Auslastung des Stromnetzes	In Cooperation with transmission system operators, distribution system operators, manufacturers of network resources, the Federal Network Agency and Associations, the German Energy Agency (dena) and the Office for Energy Management and Technical Planning (BET) have developed a catalog of measures to counteract the danger of grid congestions. The focus was on identifying short term (i.e. 2023) feasible measures that will significantly reduce the costs of network congestion management at the highest voltage level during this period. Several measures were identified. These include concrete conversion and reinforcement measures in the power grid as well as process optimization in network planning and approval procedures. [51]	
	dena-Verteilnetzstudie	The dena distribution network study has examined in detail the expansion and conversion needs in the German electricity distribution grids using two alternative expansion scenarios for renewable energies. The results show that there is a clear need for expansion for the high, medium and low-voltage as well as intermediate storage levels until 2030. [51]	
	dena-Netzflexstudie	In the "Network Flex Study", dena examines how storage systems can be used to make the electricity network more flexible. The goal is to identify operating models for storage facilities that relieve the power grid and are at the same time economical. [51]	
	dena-Netzstudie I und II	With the help of the grid studies I and II, dena presents the measures with which the German power grid can meet the requirements of the future: through targeted grid expansion while optimizing the existing energy infrastructure. [51]	
	dena-Systemdienstleistungen	Renewables, storage and other alternative contributors of alternative services should do more to contribute to the safety and stability of the power system in the future. In order to create the necessary conditions for this efficiently and on time, the dena platform system Services bundles the results of the various individual	

		activities in the field of future system operations, identifies open fields of action and promotes the exchange between experts and communication to the interested specialist public. [51]	
Switzerland	Sologrid	The aim of the project is to show how decentralized intelligence will optimize the network costs and improve the quality of electricity supply and the network. The end customer takes center stage during the entire duration of the project. A smart distribution system is not there to impose any constraints on the end consumer On the contrary, it ought to provide added value.	
	smart grid eich	35 PV power plants (160 kWp) on rooftops are controlled with a central ripple control system in order to stabilize the distribution system voltage. Reactive and active power control / curtailment	
	GridBox	Main project focus: Demonstrate the potential of a real-time grid management system on MV/LV level, grid state estimation, topology estimation, power flow optimization, provide a solid base infrastructure for any type of future smart grid application. The core concept is a highly distributed network of real-time measurement devices. All nodes within this network communicate real-time grid status information in a hierarchical manner. The grid state is continuously measured and modelled, so that appropriate control of relevant parameters is possible.	
Austria	Solarthermie – solare Großanlagen 2017 [54]	Research and planning with the topic “solar and solar thermal sources > 100 m²”	Building and planning
	Photovoltaik & GIPV [54]	Support new PV system projects	Supporting
	Photovoltaik in der Landwirtschaft [54] (engl. Photovoltaik in agriculture)	Support new PV system projects (especially agriculture)	Supporting
	Demoprojekte Solarhaus [54] (engl. Solar house)	Support houses with the aim to achieve an entire sustainable energy system	Supporting
	Klimafonds (2007) [55]	Initiator for sustainable energy technologies. Financial supporting for PV projects (overall 295,79 MWp)	Building and planning
	ERIGRID (2014) [56]	Generate an international research infrastructure for holistic hard- and software tests (Smart Grids).	Research

	Photovoltaik Roadmap für Österreich [57]	Analysis of the economic and technical potential of PV in Austria	Research
	Smart Microgrids and Renewable Energie in Smart Grids group AAU [58]	Optimize the combination of power networks and communication networks (so called smart microgrids) by self-organizing algorithms and mechanisms	Research
	en-trust (2012) [59]	Privacy, security, and user control in the smart grid user domain	Research
	Photovoltaics [60]	12 projects with different objectives dealing with the research of photovoltaics	Research
Japan	The project “PV Power Generation Control by two-way communication” started from 2015. Other national projects are planned from 2016 onwards.		
USA	Over 100s of such projects, including various utilities and private projects, such as SG demos, microgrid control, Sun Shot, EPIC, and Integrated Grid. Utility projects including roof top solar, etc.		

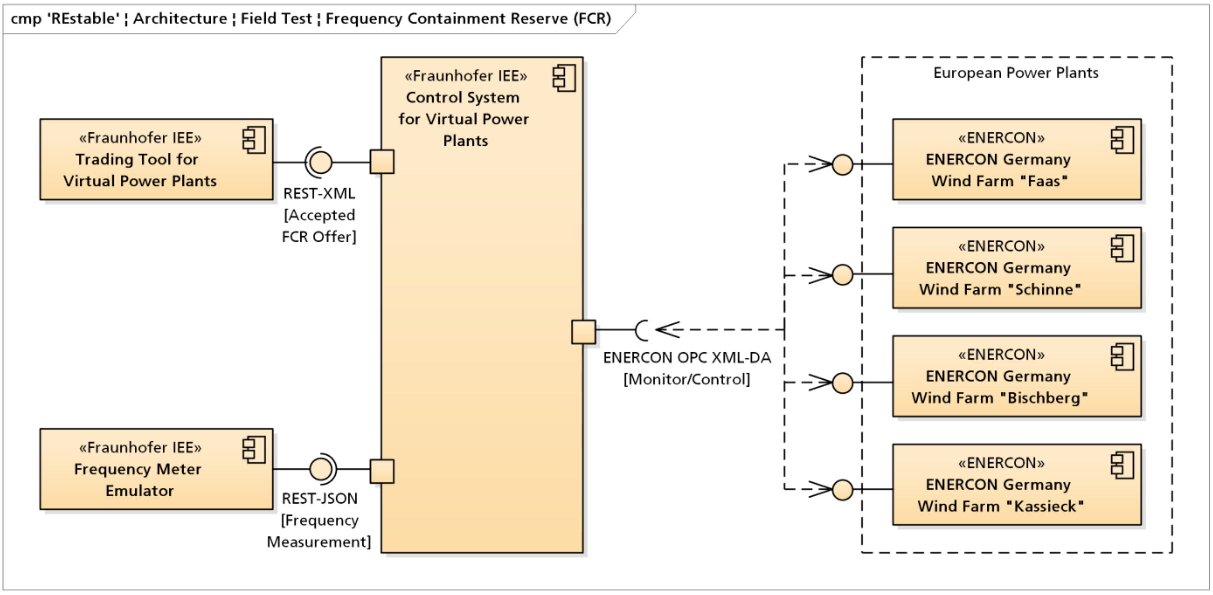


Figure 7: Schematic diagram of REstable project

5.2 Existing PV Projects with PV Communication & Control

Table 3 summarizes a list of PV projects with a description of communication and control system deployment in those projects.

Two examples of the existing microgrid systems in Greece were introduced. The microgrid system at Gaidouromantra valley, Kythnos Island was one of the first microgrid in operation since 2001. It is a 3-phase low voltage system supplying 12 houses. The main generation sources are distributed PV systems. In this example, the active power supplied by PV systems are de-rated if the system frequency is higher than 51Hz. The other example system is in the island of Crete, which is an isolated electric system with an average annual renewable electricity share of 20% and maximum renewable capacity share of 38.5%. In this example, the control centre monitor selected PV systems for accurate production predication.

In Japan, an existing project tries to develop PV inverters which can communicate with the SCADA system. The role of communication and control system in this project includes PV output control, reactive power control and collecting sales data.

The replies from USA summarized the experiences from a number of existing PV projects.

Table 3: List of existing PV projects with PV communication and control

Country	Project name	Project overview	Role of PV communication & control within the project	Description of the PV communication & control system	Lessons learned about PV communication & control
Greece	The Gaidouromantra microgrid in Kythnos island	The system is a 3-phase low voltage microgrid composed of the overhead power lines and a communication cable running in parallel. It is electrifying 12 houses with a 1-phase electrical service. The system is permanently islanded without physical connection to the public utility. The grid is formed by battery inverters. The system includes 7 distributed PV arrays with 11 kWp total installed power.	Frequency control through active power derating	If the system frequency is above 51 Hz, the PV inverters can shift out of the maximum power point of operation and derating their active power output. The PV active power output is down to zero at 52 Hz.	No complex communication system is required for a stable microgrid operation. The power from the distributed PV fields and from the user can be controlled down remotely using the grid frequency.
	The autonomous power system of the island of Crete	The Greek island of Crete is served by an isolated electric system with an average annual renewable electricity share of 20% (2012) and a maximum renewable capacity share of 38.5% (consisting of 180 MW wind power and 70 MW of PV power). The annual peak load is 650 MW.	Monitoring of status	During normal operation, PV plants provide power output without any restrictions, while wind parks contribute taking into account the maximum allowable instantaneous renewable share, which is about 40%. If this value is reached, the power output of the wind parks is appropriately reduced. The Energy Control Center of Crete monitors continuously the wind parks and a set-point for maximum power	

Country	Project name	Project overview	Role of PV communication & control within the project	Description of the PV communication & control system	Lessons learned about PV communication & control
				output is given up to every 5 minutes. The center also monitors selected PV plants at various locations in order to assess the total PV production.	
Germany	SmartSolarGrid	SmartSolarGrid (SunSpec for PV integration into SmartGrids)	Development of a standardized gateway for communication and control of PV inverters	Utilization of SunSpec protocol and IEC 61850 for information and control	Readout of values is commonly available from the implemented SunSpec protocols. Most inverter manufactures restrict write operations to their devices.
	Aktive Netzstation	Development of new technologies to increase the uptake of renewable energies in low-voltage networks	The aim of the project is to develop a technically reliable, cost-effective and easy-to-implement solution based on an adjustable local network station, which enables such an active and intelligent operation of the low-voltage network and thus the fast and economic connection of additional PV systems and other decentralized feeders allowed.	IEC-Norm „IEC 61850-7-4 Communication networks and systems for power utility automation -Basic communication structure compatible logical node classes and data object classes”	See: https://www.energiesystemtechnik.iwes.fraunhofer.de/content/dam/iwes-neu/energiesystemtechnik/de/Dokumente/Veroeffentlichungen/2014/PV-Integrated_%C3%B6ffentlicher_Abschlussbericht_V2.pdf

Country	Project name	Project overview	Role of PV communication & control within the project	Description of the PV communication & control system	Lessons learned about PV communication & control
	PV-Integrated	Integration of large shares of photovoltaics into the electrical energy supply - New methods for the planning and operation of distribution grids	The aim of the project is to facilitate a technically and economically improved network integration of photovoltaic systems in distribution grids and thus reduce the need for future grid expansion measures. For this purpose, new methods are to be developed with which photovoltaic systems, in conjunction with known and new equipment (for example storage), can be actively involved in the operation of electrical medium- and low-voltage networks and their effects on network planning can be analyzed.	Utilization IEC 61850 for information and control of PV systems. Also functionality of radio-ripple control applications for PV systems evaluated.	
	C/sells	50 Partners (TSO/DSO, Energy Service Providers, Industry and Research Institutions) showcase the digitalization of the energy system based on solar energy and flexible load in southern Germany.	The C/sells project within the SINTEG program of BMWi aims to demonstrate the capabilities of the new smart meter infrastructure in Germany.	This digitalization approach establishes a secure communication channel for the communication with DER devices based on a smart meter gateway. A PKI-infrastructure ensures the authentication of the participating devices.	The rollout of the smart meter gateways (SMGW) will start after three independent manufacturers are able to offer a certified SMGW. Bidirectional communication between DER and DSO control center based on SunSpec protocol at DER level and mapping to IEC 61850 standard have been demonstrated within smart grid test laboratories.

Country	Project name	Project overview	Role of PV communication & control within the project	Description of the PV communication & control system	Lessons learned about PV communication & control
Denmark	PVNET	The purpose of this site is to provide external information about the Photovoltaic - Smart Grid project on the island of Bornholm, DENMARK. The project was official signed with Energinet.dk June 2011 and will run until August 2016. The target for the project is to study how to integrate large amount of PV into the network, without having to reinforce the network. This is done by examining different types of grid voltage control, applying smart grid functionalities and introducing other ancillary services integrated into the PV system.	① Exploiting the grid management functions of solar PV inverters to verify the effectiveness of voltage control ② Utilize the communication capability of solar PV inverters to broaden the monitoring system of distribution grid operator	See Figure 8 for details	① Manufacturers often have their own communication protocols and data formats, standardization is important to have a common information model to ensure the interoperability and plug-and-play of PV plants. Current initiatives include IEC 61850-5, and IEC 61850-90-7 which has been mapped into the SunSpec communication profile, etc. ② Communication is an urgent issue for fully utilizing the existing functions of PV inverters. By the time of the reporting, many PV inverters have chosen open data protocol SunSpec Alliance to enhance the interoperability. This will be one of the essential problems in future in case if grid operators would like to use the inverter data for grid monitoring and observability. ③ Provided by standardised communication capabilities of PV plants, an important R&D issue is the design advanced control strategies and algorithms for integrating the control effects of many PV systems, and/or with other decentralized systems, to improve the control efficacy and reliability. Especially a

Country	Project name	Project overview	Role of PV communication & control within the project	Description of the PV communication & control system	Lessons learned about PV communication & control
					hassle-free setup of “the last mile” of communication, based on already communication infrastructure at the customers, without compromising cyber security.
Switzerland	Smart Grid Eich	A demonstration project to test the proposed ripple control based control system on PV power plants. Smart Grid Eich: only PV, about 160 kWp Location: Frenkendorf Objective: Low voltage control with PV-systems 35 PV power plants on 35 rooftops.	Ripple control, signal modulated on power lines (very low frequency, about 1 kHz). Communication over 4 relays to the power inverters.	See Figure 9 for details ripple control signal sends signal to PV power plants (signal 1 to 8), inverters use the signal to adjust their power	Communication is the one part which fails most in the system. 97% of all failures due to communication between the control center to the critical grid node.
Austria	ERIGRID 2014 [56]	As mentioned above. Furthermore, the laboratory of the AIT deals with the communication between PV and the grid. An inverter, who should be able to detect failures, is the key of this communication.		Smart grid communication with PV, inverters, loads and the conventional grid	

Country	Project name	Project overview	Role of PV communication & control within the project	Description of the PV communication & control system	Lessons learned about PV communication & control
	PV GRID (2012) [61]	"The PV GRID project followed up the achievements of the PV LEGAL project and more particularly focused on the regulatory and normative barriers that complicate the implementation of technical solutions for a better PV grid integration"		Political, administrative communication	
	EEGI Core Project (2010) [62]	Model region for Smart Grid applications.		Grid communication with cars, PV and consumers	
	IPEN	IP-based communication infrastructure for smart grid systems (incl. PV generators)		Communication with DER	
	OpenNES	Open DER-controller architecture		Communication with DER	

Country	Project name	Project overview	Role of PV communication & control within the project	Description of the PV communication & control system	Lessons learned about PV communication & control
	DG-DemoNet Smart LV Grid	Voltage control in active low-voltage distribution grids (incl. active control of DER)		Communication with DER	
Japan	-	Establishing communication technologies for PV output control (2015-2018)	PV output control for balancing; reactive power control; collecting sales data, such as time and amount of consumption	Development of inverter which can communicate with SCADA (TSO) EMS	Examination of controlled inverter, especially comparison reliability between PLC and wireless.
USA	A few	DOE smart inverter demos up to 500kW-2MW. Example projects: SRP project, APS project, NREL INTEGRATE, SHINES, CSI4, EPIC	Two way communication, monitoring of status. Standard control functions: L/HVRT, L/HFRT, max power limiting, Volt-Var, PF, Volt-Watt, Freq-Watt, ramp rates.	Usually modular with local communication to the inverter using SunSpec Modbus. Communication modems/modules are connected at the inverter and provide compatibility with various physical layer network technologies and protocols: ① Network media: Public cellular, private field area network, AMI (RF and PLC), SCADA, utility fiber, customer Wi-Fi. ② Network application layer protocols: DNP3, IEEE P2030.5, SunSpec Modbus. ③ Modular interfaces at the	① Communication with different distributed systems requires uniform standardized communication interfaces, and achieving such consistency requires certification of the communication interfaces. ② Communication control capabilities in current products are only ready with proprietary protocols and require a translator to communicate with utility systems. ③ Utilities in higher penetration areas are beginning to take advantage of grid support functions such as changing trip limit settings and location-specific or voltage-dependent reactive power from inverter. However, knowing the right settings

Country	Project name	Project overview	Role of PV communication & control within the project	Description of the PV communication & control system	Lessons learned about PV communication & control
				inverter: Ethernet for large plants, CEA-2045 for residential PV.	and obtaining certifications for these systems is still a challenge. ④ Inverter response to functional commands differs from one manufacturer to another, for example the timing of responses to control functions is not specified in any standard. ⑤ Inverter support of grid functions are immature and in some cases flawed such that the response provided is not what is needed.

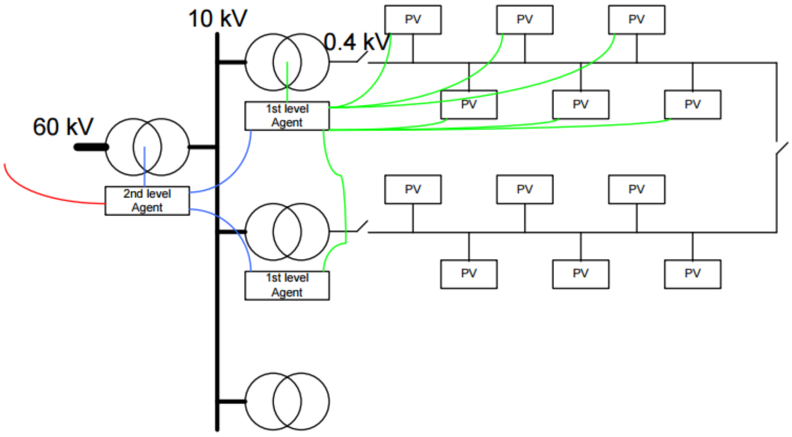


Figure 8: Assumed system layout of PVNET project. The PV systems are controlled by a local agent, 1st level agent, which communicates with the neighbouring agents in case of a ring-network and also communicates the 2nd level agent.

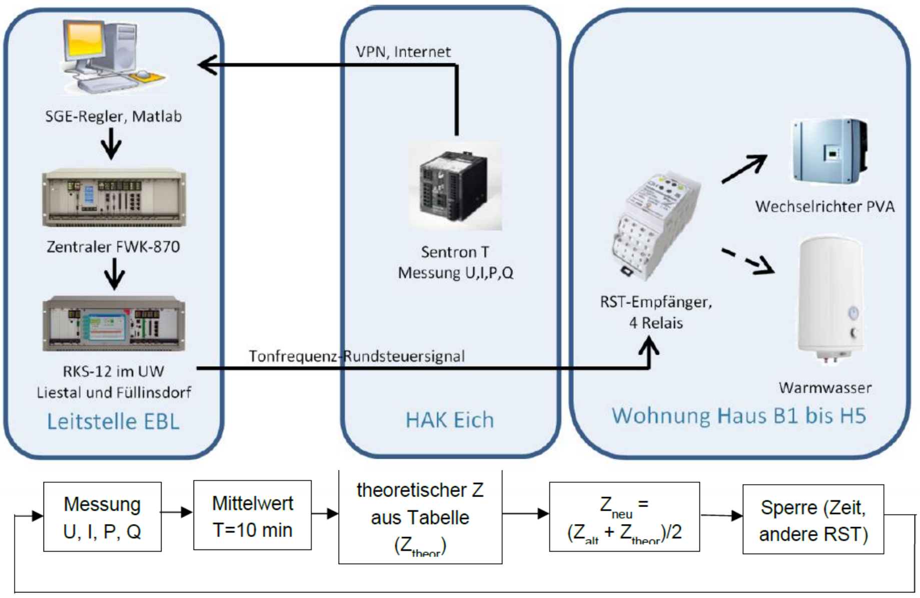


Figure 9: Control system layout of “Smart Grid Eich” project. Security: VPN tunnel for measurement signal. Offline-system for sending ripple control signals

5.3 Existing Legislations or Standards on PV Communication and Control

The existing legislation or standard on PV communication and control is summarized in Table 4. In Denmark, there is a requirement of separate production meter for PV systems and communication systems for all PV systems, but the actually use of the communication is yet to be seen. In Japan, there is only one requirement about the curtailment of PV. In the USA, a lot of action has been taken to deal with PV communication and control systems, such as the revision of the grid code for the state of California and IEEE 1547.

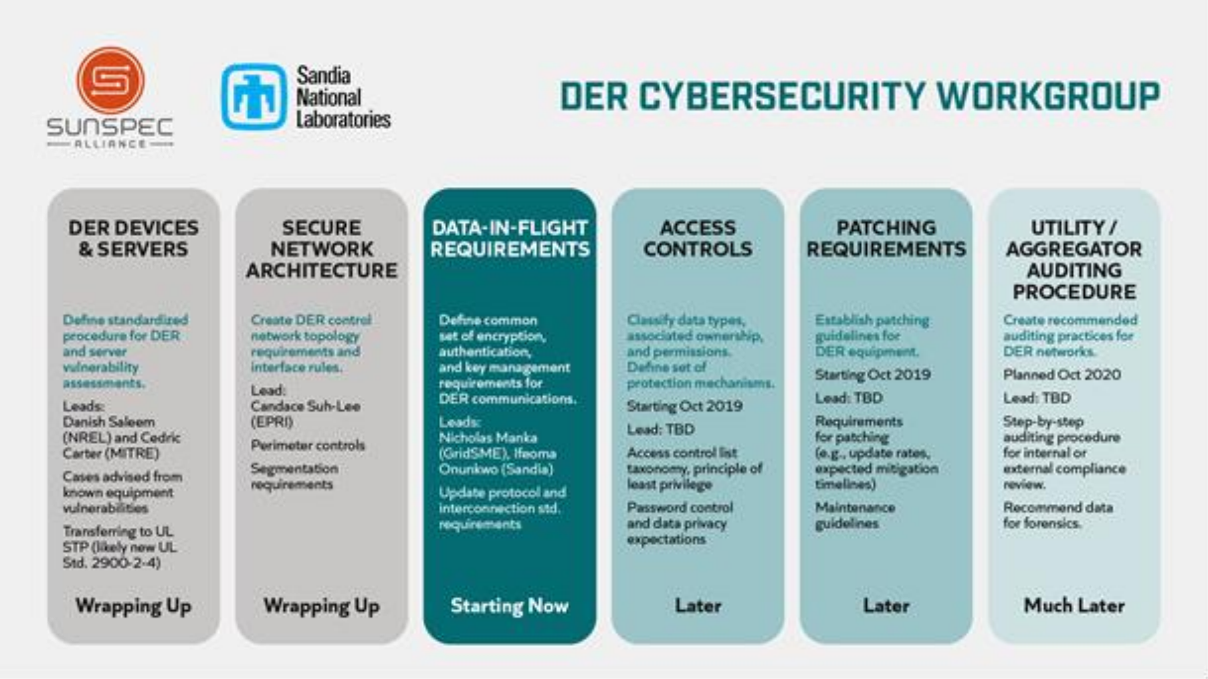
Table 4: A summary of existing legislation and standards for PV communication and control system

Country	**Existing legislation and standards for communication and control of PV systems**	**Metering of PV systems**	**Curtailment of PV systems**	**Grid operation services**	**Communication standards**
Denmark		Systems above 50 kW are obligated to have a meter installed, which registers the production on an hourly base. The meter data is collected by the utility, and the DSO then send the data to the TSO.	None	None	① PV System below 11kW must equipped with communication interface and be prepared to receive external “stop” signals and hold signal “Released to start”. The communication should comply with IEC/TR61850-90-7 and/or SunSpec alliance inverter control profile. Details can be found: http://energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/El/Teknisk%20forskrift%203.2.1%20for%20anlæg%20til%20og%20med%2011%20kW,%20rev.%202.pdf ② PV systems above 11kW must Install communication interface and be prepared to receive external “stop” signals and “Released to start”. The communication should comply with IEC/TR61850-90-7 and/or SunSpec alliance inverter control profile. For a solar cell

					system, the exchange of information must be implemented with one Protocols, as specified in IEC 61850-8-1, with a map to IEC-60870-5-104. Details can be found : http://energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/El/Teknisk%20forskrift%203.2.2%20for%20solcelleanlæg%20større%20end%2011%20kW%2c%20rev.%204.pdf
Germany	Feed-in Law (EEG)	The Renewable Energy Sources Act (EEG), which entered into force in 2000, is a key driving force for the expansion of renewable energy in Germany [47].	Yes		
	Gesetz zur Digitalsierung der Energiewende [69]	The Act on the Digitalization of the Energy Transition heralds the launch of the smart grid, smart meter and smart home in Germany [48].			Smart meter obligatory for new and already installed PV systems with installed power > 7 kWp
	Energiewirtschaftsgesetz (EnWG)	The law contains basic regulations on grid-bound energy.	Yes, curtailment of DER shifted from EEG into EnWG, effective from Oct. 2021		

	Grid Codes	Grid codes serve as a regulatory framework for the integration of DER into the electricity network	Yes	• Active power control as function of over frequency • Reactive power control as function of cos phi • LVRT	
	Marktstammdaten-register (MaStR)	A comprehensive regulatory register of the electricity and gas market, which can be used by the authorities and market operators of the energy sector (electricity and gas), is set up with the Markstammdaten-register [49].			
Japan		None	Regulation is existing for curtailment	None	None
USA	Revision of Rule 21: new grid code for the State of California requiring grid-supportive functions, monitoring and communication; UL 1741SA: revised smart inverter test procedure that includes testing of the functionality required in CA Rule 21; IEEE 1547.1-2020 now approved in USA since May 2020	Net energy metering has been adopted in 80% of states. The trend now is away from NEM to “value of solar” or to “avoided cost” basis for metered solar energy.	Not for solar yet, but under discussion	Defined in IEEE 1547-2018	Functions are well defined. Protocols are identified such as IEEE 2030.5, DNP3, SunSpec Modbus, CEA-2045, OpenADR and IEC 61850. IEEE 1547.1-2020 states IEEE 2030.5-2018, IEEE 185-2012 (DNP3) and SunSpec (model 700) but is not limited to these three. IEC 61850-7-420 mapping is also explained in Annex D

Switzerland	No "standard", but a "custom": some DSO use the German standard for active power curtailment: 4 signals, 0/30/60/100 % of maximum power output.	Metering law https://www.admin.ch/opc/de/classified-compilation/20101915/index.html	No legal basis: energy law defines that PV power plants must not be curtailed	None	None
Austria	The National DER Grid Code [63] requires communication and control of active and reactive power capabilities for only DER plants >100 kW	Currently, there are no indications that communication and control requirements will be extended. Possibly, Smart Meters will be used to monitor power output (ex-post) and delivery of grid support services.			No nationwide standards for PV control and communications exist currently. Network operators use their individual control and communication infrastructure for this purpose. In practice, technologies such as audio frequency ripple control, directional radio are being used.



DER CYBERSECURITY WORKGROUP

DER DEVICES & SERVERS

Define standardized procedure for DER and server vulnerability assessments.

Leads:
Danish Saleem (NREL) and Cedric Carter (MITRE)

Cases advised from known equipment vulnerabilities

Transferring to UL STP (likely new UL Std. 2900-2-4)

Wrapping Up

SECURE NETWORK ARCHITECTURE

Create DER control network topology requirements and interface rules.

Lead:
Candace Suh-Lee (EPRI)

Perimeter controls

Segmentation requirements

Wrapping Up

DATA-IN-FLIGHT REQUIREMENTS

Define common set of encryption, authentication, and key management requirements for DER communications.

Leads:
Nicholas Manka (GridSME), Ifeoma Onunkwo (Sandia)

Update protocol and interconnection std. requirements

Starting Now

ACCESS CONTROLS

Classify data types, associated ownership, and permissions. Define set of protection mechanisms.

Starting Oct 2019

Lead: TBD

Access control list taxonomy, principle of least privilege

Password control and data privacy expectations

Later

PATCHING REQUIREMENTS

Establish patching guidelines for DER equipment.

Starting Oct 2019

Lead: TBD

Requirements for patching (e.g., update rates, expected mitigation timelines)

Maintenance guidelines

Later

UTILITY / AGGREGATOR AUDITING PROCEDURE

Create recommended auditing practices for DER networks.

Planned Oct 2020

Lead: TBD

Step-by-step auditing procedure for internal or external compliance review.

Recommend data for forensics.

Much Later

Figure 10: Project structure and timeline (Status Jan 2019) for the secure communication with DER in a smart grid from the DER Cyber Security Working Group led by SunSpec and Sandia National Laboratories, USA. [65]

5.4 Expectations for PV Communication and Control

In Greece and Denmark there is no urgent need for the communication & control functions during PV system integration.

In Japan there is only limited need for voltage control at grid coupling points and reactive power services at the moment.

In Denmark, the installed PV capacity (MW) has not yet been a challenge to the utility network. Only a few voltage problems in the low voltage network were found, primarily due to single-phase inverters. However due to the installation of larger PV systems above 25 MW, utilities now see some fast speed fluctuations in power productions on cloudy days. In the near future, there could/will be a need of controlling larger PV plants to provide frequency and reactive power support during night time.

In Germany, the following functions are implemented: (1) Actual power monitoring at POC; (2) Voltage monitoring at POC; (3) Curtailment/feed in management of PV system. In the future, the following functions may be required: (1) Active/reactive power sharing; (2) Voltage regulation at POC; (3) Frequency regulation at POC; (4) Reactive power service at POC.

In Switzerland, the following functions are already achieved: (1) Active/reactive power sharing; (2) Voltage regulation at POC; (3) Frequency regulation at POC; (4) Actual power monitoring; (5) Voltage monitoring; (6) Reactive power service.

In the USA, the expectation for communication & control functions during PV system integration is increasing as the penetration level is rising. Considering the long service life of PV systems, it is suggested that the PV systems deployed today should be communication integration-ready. The PV communication & control functions applied in the present solar projects in USA include:

1) Active power of PV system: Required in some island systems, not yet in mainland.
2) Voltage at grid coupling point of PV system: Required in some specific feeder conditions with relative high penetration.

3) Curtailment/feed in management: Not yet required.
4) Change of frequency control characteristic, reactive power service: The need is foreseen and will be required in new standards.

5.5 Communication Media

Many communication channels have been used in the present electrical systems. A summary of the communication media can be found inTable 5.

Table 5: Summary of communication media used in various countries

Country	Communication channels used
Greece	Radio control, GSM/GPRS, power line
Denmark	The utilities usually have a pier to pier communication on a secure network based on a protocol like IEC60870-5-104 and IEC61850-90-7; Utilities uses many ways of communications for different purposes (meter reading, control of substations and relays), mainly including: radio control, GSM/GPRS, power line, TV white space, GPS
Japan	Several communication methods were tested through demonstration projects.
USA	Many physical media are in use, primarily in research projects and demonstrations: Public cellular, utility fiber, SCADA (private RF), AMI (various proprietary unlicensed RF), G3 (PLC), consumer broadband (Wi-Fi or Ethernet), field area network
Germany	GSM/GPRS, satellite based digital communication (GPS), DSL, power line, radio ripple control (small DER)
Switzerland	Radio control (not over air but as ripple control); GSM/GPRS; power line (increasing); FTTH (fiber to home) and fiber optics (increasing used, mainly for substation communication, but also for connecting power meters)

5.6 Requirements and Data Availability

Depends on the services, different time scales of data will be required. Table 6 summarizes the requirements of data availability in different countries.

Table 6: Summary of requirements for availability

Country	Requirements for availability
Denmark	The data requirement for PV systems are not in place at the moment, however with installed capacity increasing, day-ahead forecast data should be required from PV systems
Japan	The long term PV system data such as hours, intra-day and day-ahead data will be required in the near future for PV curtailment
USA	In May 2020 IEEE 1547.1-2020 “IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces” was approved which explains in detail the testing to approve network access and defines the communication requirements and protocols that should be available at all time of operation in detail.
Germany	The intra-day and day-ahead forecast data of PV system are required. PV > 100 kWp must have monitoring interface for the grid operator
Switzerland	The real-time data is required for primary control; minutes data is required for secondary control, voltage control and metering; Intra-day and day-ahead data are not directly required for PV systems

5.7 PV Communication Standards

Table 7 shows the PV communication standards and guides specified in different countries.

Table 7: Summary of PV communication standard

Country	Communication channels used
Greece	No standard
Denmark	The internal communication between inverters could be like SunSpec, but the utilities don´t allow 3rd party equipment (not utility bought) to be connected to their communication system. So in most cases an RTU will be installed in between the utility and the PV plant
Japan	the national standard will be available in near future
USA	IEEE 1547.1-2020 defines communication protocols and applications for DER connection to the electric power network. The following standards have been used: IEC 61850-7-420, IEC 61850-7-520, DNP3 AN 2013-001, SunSpec, Modbus, IEEE P2030.5, OpenADR 2.0b, and CEA-2045

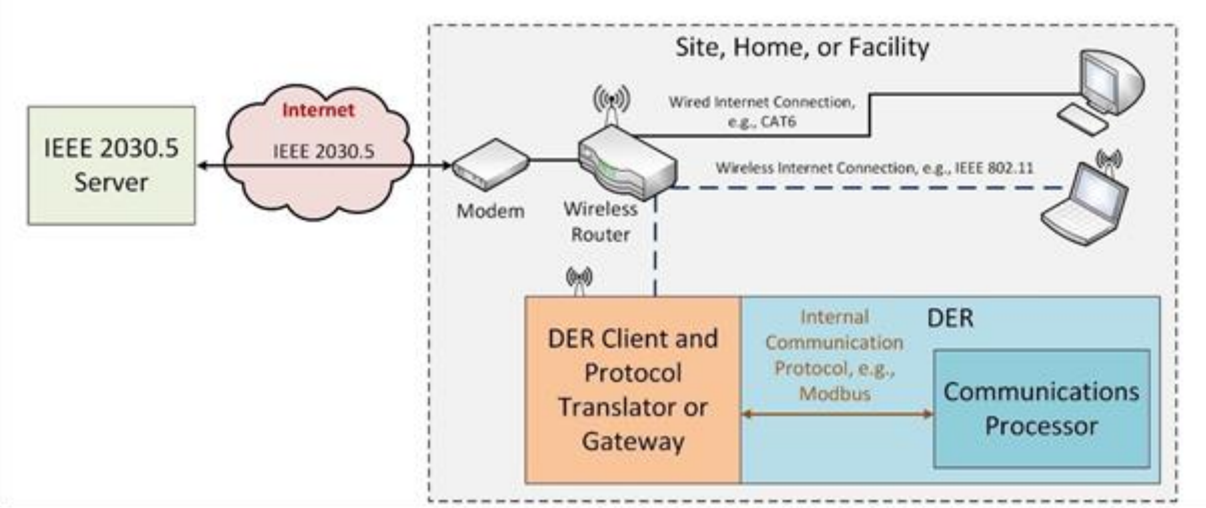


Figure 11: Communication with DER according to California Rule 21 based on IEEE 2030.5 standard [64]

5.8 Data Security

Table 8 summarizes the prevailing concerns about the data security among the different countries.

Table 8: Summary of data security

Country	Concerns on data security
Greece	Not seen as an issue.
Denmark	Existing discussions about the utility assessment of the risk letting 3rd party equipment being connected to the pier-to pier network.
Japan	Existing discussions about closed communication systems among utilities.
USA	Becoming a big issue. The primary concern is the security of the wide-area networks outside the PV plants by which large numbers of PV plants could be accessed. Local inverter modular interfaces and intra-plant interfaces at physically-secured sites is a secondary concern. The new grid cod of the state of California (CA Rule 21) already includes communication security requirements.
German	Existing issue. Currently many demonstration projects and research development are going on regarding data security. The uptake of the smart meter infrastructure in Germany will establish secure communication channels to DER systems.
Switzerland	Data security is already an existing issue.

6. CONCLUSIONS

In the conventional electrical power system infrastructure, communication systems have played an important role in some aspects, such as operation, market transactions, security and integration of large generation and distribution systems. On the distribution side, the electric network was mainly passive, operating in a feeding load scheme, with limited interaction between the supply and the loads. This required little or no communications at all. However the integration of DERs, such as solar PV system in distribution system or customer premises has motivated the development of different control strategies to take advantage of distributed and controllable resources. This has highlighted the importance of last-mile communications networks as a supporting infrastructure to allow the different modes of operation of the electric distribution network.

The increasing penetration of distributed PV systems also request for a grid-scale coordinated control network. The control paradigm of current electrical power system is slow, open-looped, centralized, human-in-the-loop, deterministic and, in worst-case, preventive [10]. At transmission level, the energy management system (EMS) coordinates system-wide decisions based on SCADA data. At the distribution level, traditional Volt/VAR control is designed mainly to cope with the slow variations in load. However, the increasing penetration of solar PV with rapid and random fluctuations implies the future control must be real-time and closed-loop. The large-scale deployment of sensing, two-way high-speed communication infrastructure and the advanced PV inverters have provided the platform to realize the distributed, real-time closed-loop control architecture in the near future.

In the previous sections, the communication and control system architecture models to enable distributed solar PV to be integrated into the future smart grid environment were reviewed. The existing communication technologies, protocols and current practice for solar PV integration are also introduced. The survey results show that deployment of communication and control systems for distributed PV systems is increasing. The public awareness on the communication and control of grid-connected solar PV systems are raising. However the actual development of communication and control system for distributed solar PV systems are still in the early stage. Many communication and technologies and control functions for distributed solar PV systems are still under experimental and demonstration phase.

In the following activities of IEA PVPS Task14 subtask C, it is necessary to review the PV projects in further details and collect the communication and control system architecture, analyse the technology and protocols and summarize the best practice for different application environment. The communication technology selection and implementation significantly affected by geographical, administrative, physical and logical reasons. The boundary conditions and transferability to other environment should be reviewed.

The major scope, objectives and the specific activities of Subtask C are defined as follows:

Scope: Subtask C addresses the communication and control for high PV penetration in distributed system with focus on the last-mile communications between customer promises to utility core communication network, i.e. the HAN/BAN and NAN/FAN.

- The last-mile communication and control requirements for different services, including data throughput, latency, reliability
- Last-mile communication standards, technologies, protocols and implementations for distributed solar PV integration
- Typical control architecture and strategies for distributed solar PV integration
- The data management, cyber security and other IT-related aspects of PV integration

Objective:

- Survey of smart grid architectures, standards on communication and control of DER
- Overview of last-mile communication technologies, protocols, interfaces
- Overview typical control requirements and architectures for high penetration of solar PV
- Overview of different practices on communication and control for integrating solar PV in distributed network
- Overview the IT-related requirements and practices for distributed solar PV integration (incl. data management, cyber security)

Activities:

Activity C.1 Collection and analysis of demonstration projects of communication and control concepts	
Durations (months)	24 months
Method/approach	• Review project report/results of various smart grid initiatives around the world • List different communication and control strategies applied in the various projects with pros & cons, while describing the boundary conditions and judge the transferability to other environments/ infrastructures • Investigate communication and control requirements for distributed PV systems
Description of work	• Research on the application of various last-mile communication technologies and protocols suitable for distributed PV systems • Review applicability and adoption of existing and future communication protocols, with a focus on IEC61850 • Identify the control requirements for coordinated operation of distributed solar PV systems. • Review the typical control strategies for distributed PV systems, such as centralized/decentralized/hybrid/distributed control
Deliverables	Qualified overview of existing communication and control concepts with a description of the environment
Target Audience	Power system operators, smart grid operators, research institutes
Milestones	Overview of typical communication technologies applied (12 month) Overview of typical control strategies applied (18 month)

Activity C.2 IT-related aspects of smart grid integration of PV, including cyber security	
Durations (months)	36 months
Method/approach	• Review of current IT-relevant discussions in the literature and among smart grid operators, including data management and cyber security • Define exact terminology for IT-relevant topics within the smart grid domain, which are relevant for PV grid integration • Collect solutions that are currently being worked on and/or are successfully being implemented in Task 14 participating countries (and beyond)
Description of work	• Engage with local communication/data security authorities for their latest rules & regulations regarding the communication within smart grids • Collect information from different Task 14 participating countries on the issuance of certificates (who is authorised for what levels?) and the way how two (or more) smart grid devices exchange certificates and ensure that they are within the same (and approved) network environment • Discuss with utility representatives the current implementation of data security inside and outside their proprietary communication environment, with a special focus on TCP/IP-based networks. • List requirements for robustness of data communication and fall-back strategies/redundant systems
Deliverables	Comprehensive overview of today’s and tomorrow’s IT aspects related to the PV grid integration in (future) smart grid
Target Audience	Power system operators, smart grid operators, research institutes
Milestones	Overview of IT-related topics relevant to PV grid integration, including data management and cyber security (12 month) Overview of data security issues and system robustness requirements (24 month) Summary of solutions for the IT topics as successfully implemented in Task 14 participating countries (36 month)

Activity C.4 smart PV grid recommendations for different kinds of infrastructure.	
Durations (months)	48 months
Method/approach	• Proposing concepts and providing recommendations on appropriate control strategies and communication technologies/protocols/interfaces • Providing inputs to standards • Reference to existing Smart Grid initiatives, such as ISGAN or SGAM
Description of work	• Qualifying and categorising the findings & results from Sub-task 5.1-5.3 to generate a matrix structure of where which type of “Smart PV Grid” would be able to generate certain types of functionalities – and under which technical boundary conditions (e.g. infrastructures) • Review and discuss the initial matrix with utilities and power system operators for a “reality check” • Verify matrix with real-world test-bed results to substantiate the robustness of the recommendations
Deliverables	Design recommendations for “Smart PV Grids”, as a function of the technical boundary conditions and depending on the desired functionalities
Target Audience	Power system operators, smart grid operators, research institutes
Milestones	Initial design & recommendation matrix (24 month) Review with real-world examples from utilities (36 month) Final recommendation matrix with qualified and categorized results that are verified with Task 14 participating countries (48 month)

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