

Update of the

SOLAR

PHOTOVOLTAIC (PV) Roadmap for Singapore



ADDENDUM

Grid mitigation measures for PV
and
Smart grid & IoT

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Smart grid & IoT

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This Addendum describes in more detail the technologies for mitigation of the impacts of the variable generation of solar PV on the electric power system, as listed in section 5.6.2 of the Update of the PV Roadmap for Singapore. Beyond that, it also provides insights of how future smart grids and IoT could facilitate PV grid integration, while keeping an eye on cybersecurity.

Table of Contents

Add-2.1	Grid mitigation measures for PV.....	2
Add-2.1.1	Supply & Demand-side management	2
Add-2.1.2	Energy Storage Systems	7
Add-2.1.3	Grid upgradation	11
Add-2.1.4	New Equipment	11
Add-2.2	Smart grid & IoT.....	14
Add-2.2.1	Smart grid & IoT for PV grid integration.....	14
Add-2.2.2	IoT technologies and their impact on the cost of PV grid integration.....	15
Add-2.2.3	Cybersecurity considerations for PV grid integration.....	17

Front cover: PV and storage installations at the Renewable Energy Integration Demonstrator Singapore (REIDS). Photo credit: NTU Singapore

Add-2.1 Grid mitigation measures for PV

This section analyses the mitigation measures required for grid impacts identified and analysed in the previous section for ensuring the stability and reliability of the grid under different scenarios.

Grid Integration measures can broadly be categorised in four different types:

1. **Supply & Demand-side management** (including flexible conventional generation and forecasting) – whether centrally controlled, or via incentives for user response to system needs. This would represent the lowest cost option for balancing the system.
2. **Energy Storage Systems (ESS)** – Energy storage is a net consumer of electricity due to efficiency losses but it enables greater PV penetration by shifting energy from periods of low demand to periods of high demand, which reduces curtailment and eases integration challenges.
3. **Grid Upgradation with Smart Grid and IoT based technologies** – this would be a software-led solution, but would constitute a 2-3-year program to (i) implement models and algorithms to introduce self-healing capability and outage management, (ii) re-align the historical “hierarchical” architecture of the grid to allow multiple distributed generation, storage and demand points to transact with each other, and (iii) create the transactive platforms to enable them to do so. Aside from providing robustness / stabilization to the grid, application of Smart Grid and IoT based technologies can lead to substantial reduction in consumption as well as losses.
4. **New Equipment** – depending on the specific characteristics of the grid, the residual grid stabilization needs can be addressed with hardware solutions at both central and local levels

It should be noted that very few of these solutions are exclusive to any one of the problem statements outlined in the Technical Report (i.e. demand profile and ramp rate impact, distribution network impact, system inertia & reserve requirements and protection system impact). In fact, several of the identified solutions bring the advantage that they can address multiple problem statements, thereby improving their cost-efficiency. The following sub-sections describe these solutions in more detail.

Add-2.1.1 Supply & Demand-side management

At its crudest level, Supply or Demand-side management simply translates into switching off parts of the grid – what is often referred to as “load shedding”, or curtailing power generation sources that would otherwise be operating economically at that point of time. But this is simply a measure of last resort to isolate grid stability issues post-event and protect the wider power system. So looking beyond these extreme cases, following a few different measures for grid management that are either centrally controlled, or which include contractual incentives for users to respond to market signals:

- **PV Curtailment:** Curtailment is the act of reducing or restricting energy delivery from a PV plant (or any generator) to the electrical grid, typically on an involuntary basis. Curtailments can significantly impact the revenue of solar PV projects. However, with the sharply declining PV prices in comparison to Energy Storage costs, it may make sense to oversize PV plants and reduce the amount of energy storage.

In a recent study, it has been shown how providing round-the-clock energy from wind and solar with storage only remains far more expensive than ‘grid parity’ (here: compared to the cost of natural gas-supplied power). But storage combined with excess wind and solar that is curtailed about 30% of the time can be less expensive than grid parity and deliver power on demand [1]. Figure Add-2.1 shows the comparative Levelised Cost of Energy (LCOE) for various scenarios of the study.

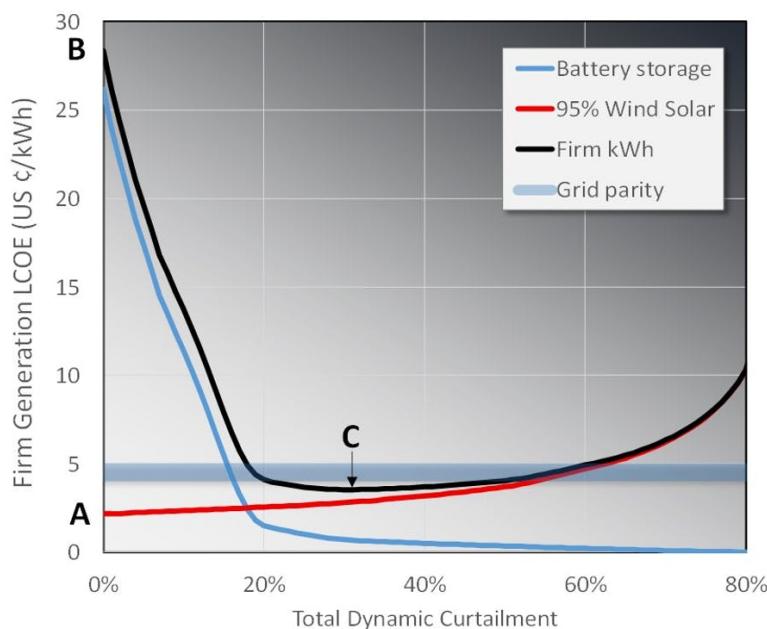


Figure Add-2.1: LCOE for different scenarios with different levels of curtailment [1].

PV curtailment can be accomplished by the use of smart inverters or by disconnecting some of the inverters in a PV plant.

However, in order to make PV curtailment a viable option for mitigation of the grid impacts, suitable regulatory/policy mechanisms need to be developed that can ensure suitable compensation to the PV plants for curtailment so as to mitigate any impacts on the business case due to the loss of the revenue. The proposed IPM (intermittency pricing mechanism) in Singapore regime promotes energy storage over oversizing PV to accommodate curtailment.

- **Flexible Conventional Generation:** Flexible power plant operation can take many forms, from rapidly changing plant output, to starting and stopping more quickly, to turning plant output down to lower levels without triggering a shutdown. The flexibility of power plants is determined by the following main parameters [2]:

- Stable operating range: This refers to possible generation levels that can be chosen, given a long lead time. The minimum stable output of the power plant is the lower bound of the stable operating range, while the maximum output is the upward constraint. The larger the stable operating range, the more operationally flexible the power plant.
- Ramp rate: This is the speed at which output can be adjusted upwards or downwards within the stable operating range. Upwards and downwards ramping rates vary depending on the plant's technical characteristics and the technical attributes of the control system.
- Minimum up and down times: These are the time constraints within which generating units have to a) remain on-line once they have been synchronised onto the system (minimum up time) or b) remain off-line once they have been decommitted (minimum down time). These constraints are due to the technical limits as well as economic factors of conventional thermal generation technologies. For example, if a conventional power plant has been dispatched to start and is followed by an unexpected decrease in demand or increase in variable renewable energy output that eliminates the need for the plant some hours later, limited flexibility is available since the conventional plant has to be operated at the specified minimum up time.
- Start-up time: This is the required advance notice to make generation available, i.e. the time necessary to reach the minimum stable output level. The start-up time can be further categorised into cold, warm and hot start-up, which is based on the operational status of power plants at the time. These relate to the temperature of the plant and depend on the time between operation cycles (a thermal plant will remain hot for several hours after shutdown). Cold start-ups take the most time, while hot start-ups can be significantly shorter. During the start-up period a plant is not available to provide services. For example, a coal-fired plant with an 8-hour minimum downtime, an 8-hour start-up time, and an 8-hour minimum uptime, is operationally constrained for these 24 hours.

Different strategies towards flexible conventional generation could be as follows:

- Use of new and innovative technologies such as advanced “F-class”, “H-class” and “J-class” Combined Cycle Gas Turbines (CCGTs). EMA is currently undertaking a study on facilitating the deployment of new and innovative conventional generation technologies¹.
- Use of multiple smaller/modular power plants instead of few large power plants
- Use of lower-efficiency Open Cycle Gas Turbine (OCGT). OCGT are more flexible than CCGTs, but the flexibility comes at the cost of >10% efficiency loss.
- Flexibility improvement of existing conventional power plants, which can be accomplished by a range of strategies broadly categorised in the following two areas [2]:

¹ See: https://www.ema.gov.sg/ConsultationDetails.aspx?con_sid=20190612EFmFVo1DKztC .

- Changes to operational practices for existing plants. Significant new capital investments are not necessarily required to operate power plants more flexibly. Changes to certain plant operational practices – often enabled by improved data collection and real-time monitoring – can be used to unlock latent flexibility in existing plants.
- Flexibility retrofit investments for existing plants. A range of retrofit options are available to improve the various flexibility parameters of power plants. For instance, combined-cycle power plants have different avenues for improvement in operational flexibility. These include changes to the design of the heat recovery steam generator (HRSG), steam turbine and the balance of plant. Newer combined-cycle plants can also be operated flexibly, either through a gas bypass – from the gas turbine exhaust to the stack – or through a steam bypass –from the HRSG to the condenser. This makes it possible for a CCGT to run in OCGT mode during fast start-up transients. The Mainz Wiesbaden CCGT plant in Germany was originally built in 2000 for baseload operation; it has been successfully retrofitted to operate in a more flexible cycling mode.

Use of flexible conventional generation can be beneficial as compared to other mitigation measures such as energy storage systems for meeting the daily ramp requirement. However, ESS have the additional advantage of applicability for providing Fast Frequency Response (FFR).

There is dearth of data on cost-benefit analysis of flexible conventional generation plants versus energy storage systems. But, the rapidly decreasing cost of Li-ion batteries coupled with their wider application in mitigating grid impacts would make them a preferred choice over the conventional generation plant. Though it needs to be understood that decarbonising the power sector requires, on the one hand, decreasing the share of thermal generation, and, on the other hand, increasing system flexibility. Therefore, there will always be merits in pushing for more flexibility in conventional generation.

- **Solar Forecasting:** Forecasting of solar output consists of a variety of methods based on the time frame being forecasted, the data available to the forecaster and the particular application of the forecast. The methods are broadly categorized in Figure Add-2.2 according to the time horizon in which they generally show value. Methods include Numerical Weather Prediction (NWP) and Model Output Statistics (MOS) to produce long-term forecasts, as well as blending techniques that combine ensemble forecasts, Statistical Learning Methods, Machine Learning Methods and Climatology [3]. EMA is developing the solar forecasting capability for Singapore.

By accurate solar forecasting, especially for short-term, i.e. periods of the order of the dispatch interval (currently 30 minutes for the case of Singapore), the PV power fluctuation can be mitigated significantly without the requirement of energy storage.

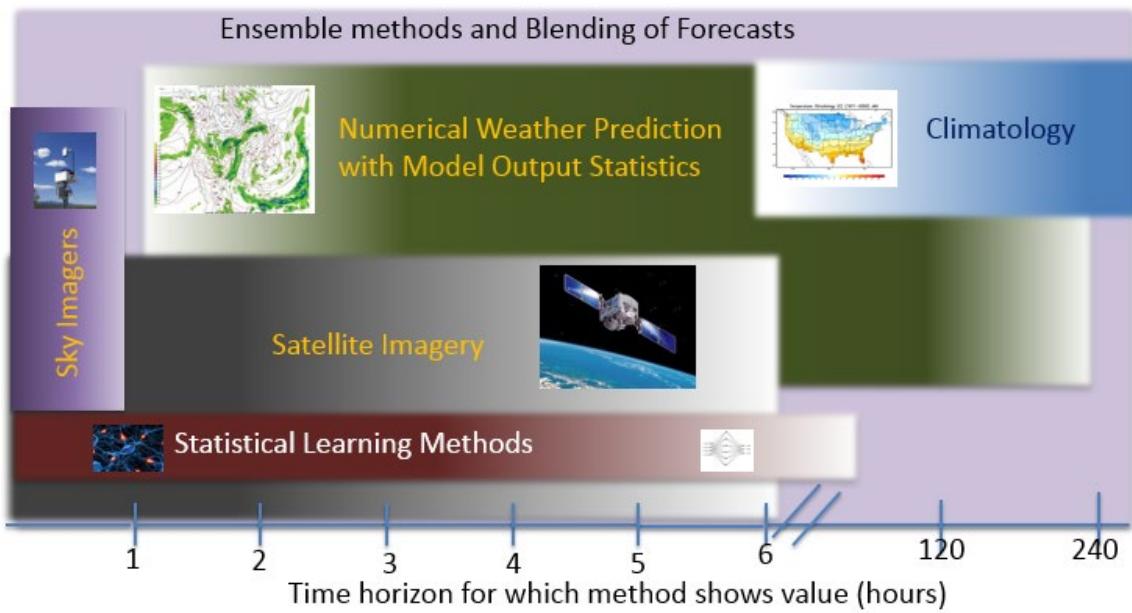


Figure Add-2.2: Generalized view of Solar Forecasting methodologies based on the time horizon for which they are suitable [3]

- **Geographical Smoothing and PV fleet management:** The challenges due to the intermittent nature of PV generation could be mitigated using optimal design and efficient management of the fleet. Siting and sizing of PV in the distribution network requires design considerations, which take into account feeder losses, voltage profile, cost, line capacity and any existing PV installations. The different correlation in the Global Horizontal Irradiance (GHI) of different PV sites could help in minimizing the variability effect (different ramp rates) at the net output of the aggregated sites. Small correlation values lead to less effect of variability in the output of the aggregated PV sites and higher values lead to high effect of variability at the output of the aggregated sites. This phenomenon in large scale PV systems is known as geographical smoothing of the PV power output.

This approach, though greatly successful in larger geographies such as Australia and USA, may not be as successful in Singapore. EMA has studied historical solar irradiance data (in per minute sampling) measured by widely spread solar irradiance sensors across Singapore and found a relatively high level of correlation among the measurements [4].

- **Energy Demand Management:** This can fall into two categories
 - **Energy usage limiting:** Use of smart metering or pre-paid meters to manage the level of consumption
 - **Time-of-use pricing:** Thereby incentivizing changes in demand curve shaping without any customer-specific contractual demand response arrangements. At its most basic level, pricing has historically been split into “peak” and “off peak” levels. But with increasing solar penetration resulting in phenomena such as the “Duck Curve”, the traditional distinction between “peak” and “off-peak” has lost its meaning. One could therefore expect to see more granular price intervals.

- **Demand response management:** This comprises contractual incentives for users with varying levels of optionality, depending on the type of ancillary services being provided. The various levels of optionality would include the following:
 - **Direct load control:** The Grid Operator has the option to directly control and switch off large pieces of equipment at the user end to curtail demand (the difference with “load shedding” being that the user contractually gives the Grid Operator the optionality to do so) – typically used for Frequency Management and Fast Response.
 - **Interruptible load:** A second class of solutions involves an option for the Grid Operator (for a specified number of times per year) to directly contracted users to curtail loads within a given response time and for a specified period – typically used for Fast & Standing Response.
 - **Interruptible load with double-optionality:** A third class of solutions could also give the users a further layer of optionality on whether to respond to the Grid Operator’s request.

Add-2.1.2 Energy Storage Systems

Energy storage systems of different kind can lead to the most substantial improvement in both EMPR (Estimated Maximum Power Reduction) and EORR (Expected %-age Output Reduction Rate) of PV systems.

Energy storage technologies are typically characterized by their applications, often in terms of discharge time. Three common categories are provided in Table Add-2.1 [5].

Figure Add-2.3 shows the general range of energy storage technologies along with typical sizes and suitable application [5].

Table Add-2.1: Three classes of energy storage

Common Name	Example Applications	Discharge Time Required
Power quality and regulation	Transient stability, reactive power, frequency regulation	Seconds to minutes
Bridging power	Contingency reserves, ramping	Minutes to ~1 hour
Energy management	Load leveling, firm capacity, T&D deferral	Hours

CAES	Compressed air	Ni-Cd	Nickel-cadmium
EDLC	Dbl-layer capacitors	Ni-MH	Nickel-metal hydride
FW	Flywheels	PSH	Pumped-storage hydropower
L/A	Lead-acid	VR	Vanadium redox
Li-Ion	Lithium-ion	Zn-Br	Zinc-bromine
Na-S	Sodium-sulfur		

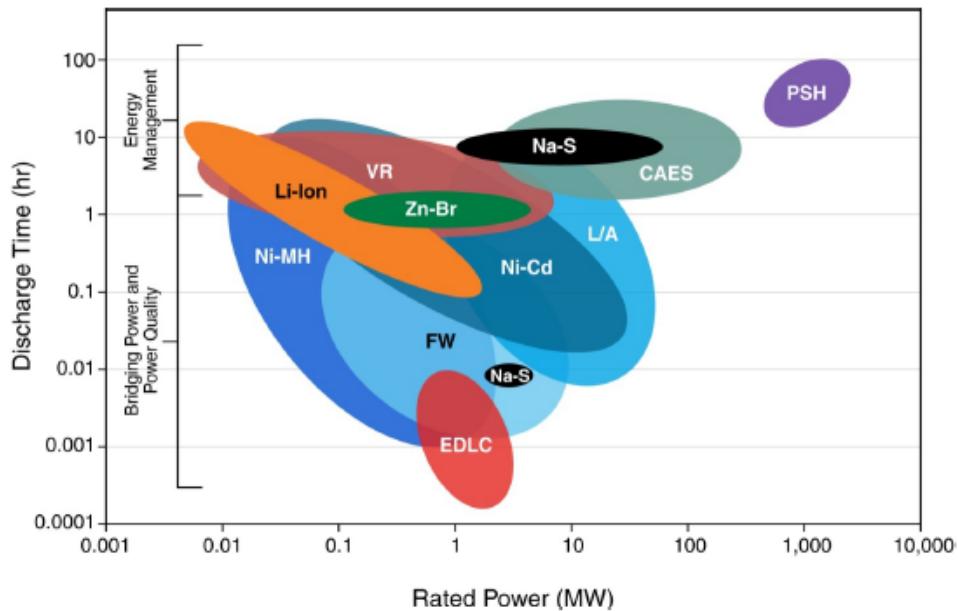


Figure Add-2.3: Energy storage applications and available technologies

The field of ESS is a vibrant and rapidly developing field and a number of storage technologies have been piloted across the world. Table Add-2.2 describes some of the common ESS technologies from the point of view of energy storage mechanisms [6].

Table Add-2.2: Common energy storage technologies

ESS Technology	Description
Pumped Storage Hydro (PSH)	Water is pumped from a lower reservoir to a reservoir at higher elevation during off-peak periods. Subsequently, when energy is needed, the water is allowed to flow back down to the lower reservoir through a turbine and generate electricity in the process.
Flywheel Energy Storage	Flywheels are mechanical devices that spin at high speeds, storing electricity as rotational energy. The energy is released later by slowing down the flywheel's rotor, releasing quick bursts of energy (i.e. releases of high power and short duration).
Compressed Air Energy Storage	Air is compressed and stored in underground caverns or storage tanks. The air is released later to a combustor in a gas turbine to generate electricity during peak periods.
Chemical Batteries	Chemical reactions with two or more electrochemical cells enable the flow of electrons. These include lithium-based

	batteries (e.g. lithium-ion, lithium polymer), sodium sulphur, and lead-acid batteries.
Flow Batteries	Electricity is produced by dissolving two chemical components in an electrolyte separated by a membrane (e.g. vanadium redox flow battery).
Thermal Energy Storage (TES)	Thermal energy is stored by heating or cooling a storage medium so that the stored energy can be used later for heating or cooling applications and power generation.
Super Capacitors	SuperCapacitors, or, Electronic Double Layer Capacitors (EDLC) are large capacitors that can be used to store energy. They offer the advantage of very fast charge and discharge time and are often used in conjunction with battery based ESS.

Beyond those options, with increasing numbers of Electric Vehicles (EV), “vehicle-to-grid” (V2G) systems that use the batteries of EVs as energy source to meet short-term energy demand have also been developed and used successfully.

Hydrogen energy storage systems comprising of an electrolyser, storage tanks and either a fuel cell or combustion technology to produce energy from hydrogen is another promising storage technology.

Limitations of ESS [6]

Cost: The commercial viability of ESS will be dependent on market forces and the ability to leverage on multiple revenue streams from different applications. Due to increase in demand, the costs of ESS have been consistently falling. As an example, Figure Add-2.4 shows the reduction in Li-ion battery pack prices (in USD) since 2010 (largely driven by the electro-mobility sector).

Losses: ESS technologies will incur net energy losses from the charging and discharging process. As ESS technologies have different levels of efficiencies, this results in varying levels of energy losses. Hence, ESS technologies with higher efficiencies will be naturally incentivised for adoption and participation in the market.

Technical Limitations: ESS can be used to provide fast or sustained response. For fast response, the ESS will need to be able to ramp up/down its power output quickly, dependent on the power output rating and achievable ramp rates. For sustained response, this will depend on the energy storage capacity and efficiency of the ESS.

Safety: ESS may pose safety concerns. For example, some types of ESS such as lithium-ion batteries may pose fire hazards due to thermal runaway. The US National Fire Protection Association is currently reviewing fire safety standards for ESS and has published a draft



Figure Add-2.4: Cost development of Li-ion battery pack price in USD

version of the Standard for the Installation of Stationary Energy Storage Systems (NFPA 855) for public consultation. Mechanical forms of ESS such as flywheels could also result in safety concerns due to the stored rotational energy, if not properly and safely controlled. Hence, some ESS technologies may need to be further researched and investigated to ensure that safety is not compromised.

Future Concentration Risk: Currently, ESS are most widely used in markets to provide frequency regulation and spinning reserves. If ESS proliferates in Singapore for the same types of services, there is a need to watch for potential concentration risk, if conventional power plants (such as CCGTs) are replaced by a few large ESS to provide reserves.

Table Add-2.3 shows some of the different ESS types in operation in the USA [5].

Table Add-2.3: Examples of deployed energy storage systems in the USA

Technology	Primary Application	Size (MW)	Owner/Developer	Location(s)
PSH	Load leveling/firm capacity/ancillary services	>40,000	Various	Various (see Figure 12-9)
CAES	Load leveling/firm capacity/ancillary services	300 PG&E ^c 150 NYSEG ^d 2,700 FirstEnergy ^e		Kern County, California Reading, New York Norton, Ohio
Sodium-sulfur (NaS) battery	T&D deferral/congestion relief	1 AEP ^f 2 AEP 4 AEP 1 Xcel Energy ^g		North Charleston, West Virginia Bluffton, Ohio Balls Gap, West Virginia East Busco, Indiana Presidio, Texas Luverne, Minnesota
Vanadium redox battery	T&D deferral/congestion relief	0.25 Pacificorp		Moab, Utah
Lithium-ion battery	Frequency regulation	1 AES/PJM Interconnection		Valley Forge, Pennsylvania
Flywheel	Frequency regulation	20 Beacon ^h 1 Beacon 1 Beacon		Stephentown, New York Groveport, Ohio Tyngsboro, Massachusetts

Add-2.1.3 Grid upgradation

A second set of measures involves strengthening the grid via software enhancements. DERMS (Distributed Energy Resource Management System) can be perceived as a DER-focused utility-support management tool with the following major functionalities: (i) models and algorithms to introduce self-healing capability and outage management, (ii) re-alignment of the grid architecture from “hierarchical” to “heterarchical” to allow multiple distributed generation, storage and demand points to interact on a level footing, and (iii) the transactive platforms to enable them to transact with each other.

Figure Add-2.5 visualises the role of DERMS in a future grid architecture.

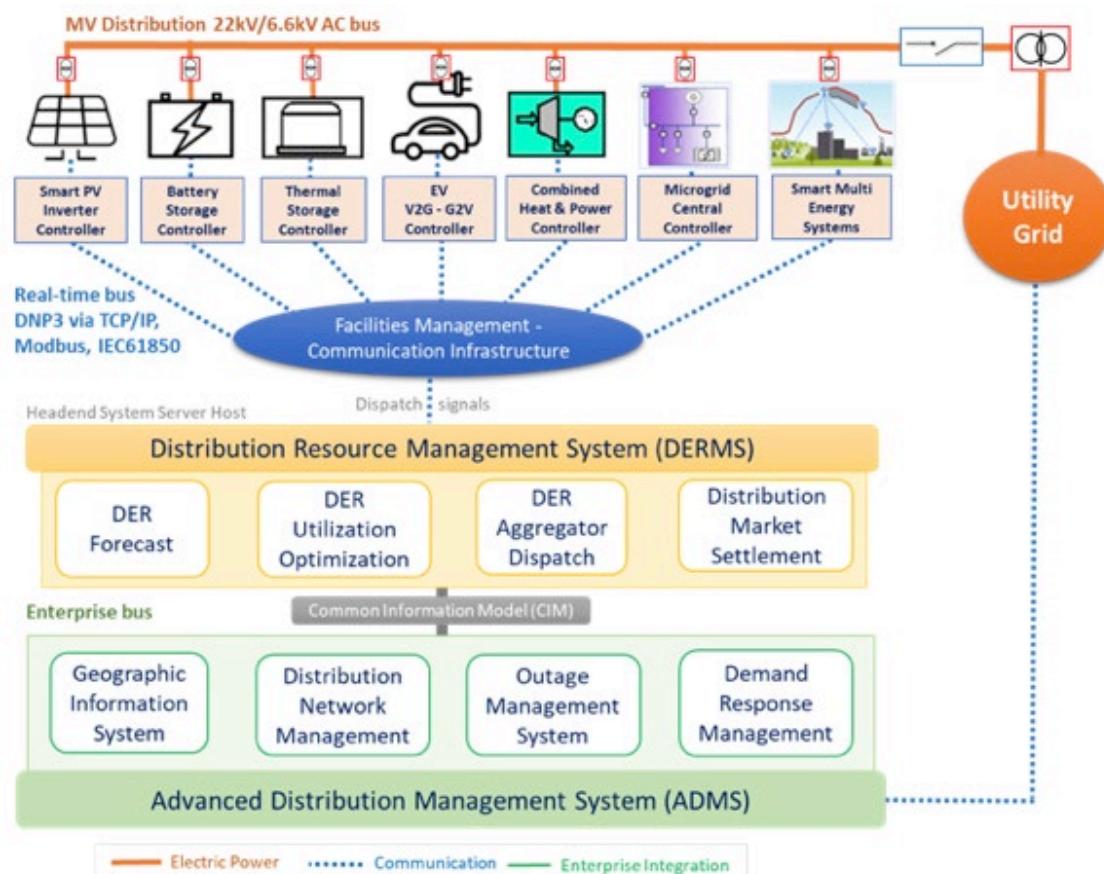


Figure Add-2.5: DERMS (Distributed Energy Resource Management System) as part of a future power system architecture.

Add-2.1.4 New Equipment

- **Smart Transformers:** This includes independent operation for voltage regulation and remote governing of power supply and transformers. Any fluctuations in a power grid is managed by smart transformers by providing instantaneous supply of required power, thereby also leading to optimized voltage regulation. Solid State Transformers are a special class of transformers still under development that are critical for bi-directional grids. They are smaller and more efficient than regular transformers as they operate at a higher frequency and can actively regulate voltage and current.

- **Static Compensators:** Static synchronous compensators (STATCOMs) are shunt-connected FACTS (Flexible Alternating Current Transmission System) devices. They are the static counterparts of the rotating synchronous condenser, however generate/absorb reactive power at faster rates, as there are no moving parts involved. They are operated as static Var compensators whose capacitive or inductive output currents are actively managed to control the bus voltage with which it is connected. In principle, they perform the same voltage regulation as the static Var compensator (SVC), but in a more robust manner because, unlike the SVC, their operation is not impaired by the presence of low voltages. They can be combined with advanced energy storage facilities, which opens the door for a number of new applications, such as energy deregulations and network security.
- **Dynamic Voltage Restorers:** Dynamic Voltage Restorers (DVR) are used to protect high power installations against voltage sags, which may lead to break in operation and large economic losses in industrial applications.
- **Smart Inverters (UL 1741 compliant):** Smart inverters can enable more efficient integration of distributed energy resources (DERs). Smart inverters go beyond the basic function of the conversion of direct current to alternating current and provide grid support functions, such as voltage regulation, frequency support and fault-ride-through (FRT) capabilities.
- **Minimum Import Relays:** The minimum import relays are relays that are designed to disconnect grid-tied PV connected systems whenever their output falls below a particular threshold value. They are also used to trip the grid-tied PV system from the network, in case their output goes above the 25% of the actual service load.
- **Reverse Power Flow Relays:** The reverse power flow relay is a directional protective relay that prevents power from flowing in reverse direction. The relay is used in installations where a generator runs in parallel with the utility or another generator so as to prevent power from the bus bar or another generator from flowing back to the active generator when its output fails. The relay monitors the power from the generator and in case the generator output falls below a pre-set value, it quickly disconnects the generator coil to avoid power from flowing into the stator coil.
- **Synchronous condensers:** Synchronous condensers (SCs) are rotating electrical machines similar to synchronous generators. They are not a generator because they are not driven by an engine and they are not a motor either because they do not drive any load. They provide additional short-circuit power to strengthen the grid and maintain power quality. They also provide fault-ride-through capabilities. They are being increasingly used by network operators and Renewable Energy developers, especially in southern Australia.
- **Virtual Synchronous Generators:** A way to stabilize the grid frequency in the absence of adequate rotational inertia from synchronous generators is to add virtual rotational inertia in the system. A virtual inertia can be attained for any generation system by adding a short-term energy storage combined with suitably controlled power electronics converters to it. Such a system behaves like a "Virtual Synchronous Generator" (VSG) during short time intervals, and contributes to stabilisation of the grid frequency.

- **DC-link capacitors in Power Converters:** While the primary function of DC-link capacitors is to provide energy storage during hold up time, they are often needed to allow fast and efficient switching of the semiconductor by minimizing the required area. Consequently, the DC-link capacitor size determines the package of a motor inverter. A compact or miniaturized DC-link can be created by optimizing the connection with a high current handling capability and a low self-inductance. Stresses including thermal, electric, environmental and mechanical – some of which have been unforeseen due to new designs and size requirements – must be planned for and designed in. Accordingly, advances in DC-link capacitor technologies have to focus on the demands of future power electronics.

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Add-2.2 Smart grid & IoT

Add-2.2.1 Smart grid & IoT for PV grid integration

The evolution of supervisory control and data acquisition (SCADA) systems and smart meters embedded with information and communication technology (ICT) like geographical information systems (GIS) and enterprise resource planning (ERP) systems have led to an increasing adoption of the Internet-of-Things (IoT) in the power sector. The three main applications of IoT in that domain are: asset performance management, grid optimisation with renewables and storage, and increased energy efficiency [1]. Using IoT for solar applications can resolve many of the complex challenges associated with power grids and facilitate better PV system monitoring and energy output control. Deploying an IoT platform for solar systems can lead to benefits for both the energy producers and utility companies by providing visualisation and monitoring tools with data analytics for managing power demand and energy flow optimisation.

Using IoT and Big Data for PV grid integration can improve the efficiency and reliability, provide operation and maintenance, real-time data, and facilitate the inspection of equipment involved. Apart from providing real-time updates, IoT can also assist with respect to metering components to track data. The efficacy of metering can be improved by using a dedicated link gateway or by having a separate module in the inverter. Implementing security solutions for IoT concepts, however, is a “must”, as firstly, the gateways (e.g. smart meters, real-time data modems) could be target of an attack to enter into the power system OT platform; and secondly, the transmitted grid and PV data are highly sensitive by themselves. Leading IT companies such as Google and Microchip have developed security solutions specifically for PV applications. Google is offering a dedicated token signed by a private key that is connected to the Google Cloud IoT Core, which can be further validated using their own key pair in order to encrypt the device communications [2].

Establishing PV energy routers (or “smart meter gateways”) on the basis of IoT, helps to reduce costs by applying intelligent sensing and cloud computing using big data analytics. It also allows to collect data from, and interaction with PV devices in a timely manner (if required even in real time). As such, IoT helps to improve reliability of PV devices and increase the output of electricity power, as shown in Figure Add-2.6.

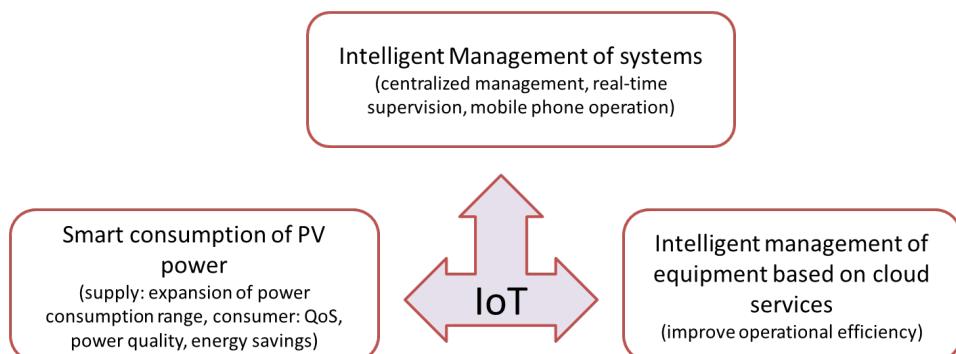


Figure Add-2.6: Overview of the role of IoT in PV grid integration¹

¹ Source: ECE, based on: Z. Tan, Q. Tan, M. Rong, Analysis on the financing status of PV industry in China and the ways of improvement, Renewable and Sustainable Energy Reviews, Volume 93, 2018, pp409-420.

Add-2.2.2 IoT technologies and their impact on the cost of PV grid integration

In this sub-section, different IoT technologies and their impact on the cost of PV integration are discussed. In relevance to the case of Singapore, some of the mitigation measures for PV grid integration, where IoT can play a role, are:

- Energy storage;
- Demand response; and
- Smart protective relays.

Energy storage

Considering the case where ESS are used as a measure for improving the demand profile impact, IoT can be implemented for ESS monitoring, cloud energy management and for data acquisition. In residential solar powered systems, IoT can be used to automate the local actions and create local intelligence. For example, a local intelligence device can be incorporated in the solar power inverters for control and management purposes. Similarly, in a number of other devices associated with the residential solar power systems such as ESS smart modules can be built for interoperability, collaboration and integration of the solar power systems within an IoT ecosystem. IoT-enabled storage systems for solar power applications can be efficiently and reliably combined energy data management systems. However, it is then necessary for the remote monitoring systems to have a reliable internet connection. One way of ensuring reliable internet connections is to equip the devices with multiple networking interfaces such as Wi-Fi, Ethernet and LTE, though this may incur additional cost.

A generic example of a IoT computing platform for data acquisition applications in solar power systems [3] is shown in Figure Add-2.7. This system comes with serial input output ports, Ethernet LAN ports and mini sockets to support cellular modules. Multiple communication interfaces namely Wi-Fi, LTE (4G/5G) and Ethernet are provided for reliability and versatility. The smart gateway system possesses a Modbus library for integration with remote I/O units for ensuring optimal system operation and status updates, such as monitoring battery charging/discharging status, managing system temperature and detection of intrusion. The data acquisition software can be used to manage the data-oriented IoT applications. The major cost of the IoT platform for solar power systems with storage involves the cost of the IoT gateway, cost of the software platform and the cost of the Ethernet I/O. Further improvements in the stated solution can include more edge-computing platforms to offer user programmable gateways for IoT applications.

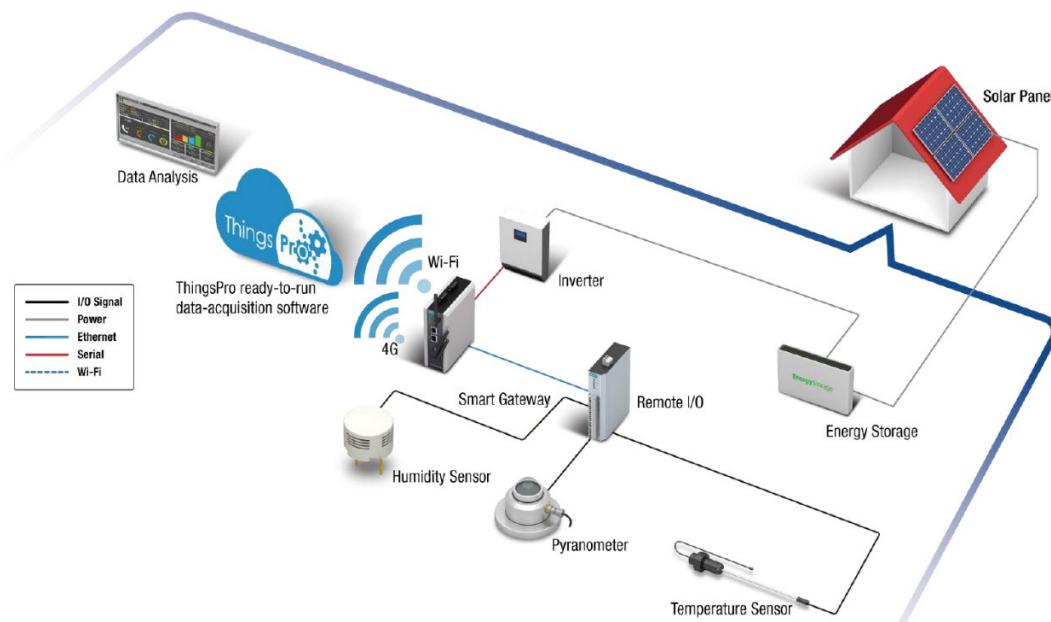


Figure Add-2.7: IoT computing platform for residential solar power system [3]

Demand response

For the purpose of reserve requirement, particularly Demand Response management, IoT can be implemented for smart appliances and advanced metering infrastructure (AMI) and/or smart meters. IoT-enabled AMI is becoming very popular on the consumer side as it allows to monitor energy consumption and assert more control over it. For the case of Singapore, for example, EDMI Limited, a global smart metering solutions provider, has partnered with Arm to deploy IoT-enabled metering devices [4]. Meanwhile, it creates opportunities for utilities to interact with the customers to encourage them to participate in demand response programs. The type of functionality (remote meter programming, time-based rates etc.) and type of programs (bill payment, demand response programs, service request portal) need to be decided by the utility for selection of a suitable AMI. In terms of connectivity, a variety of standards such as low power wide area network LPWAN, LTE (4G/5G) are available to choose from.

Cellular services (3G/4G/5G) are also viable choices for AMI initiatives, depending on the use cases and needs. According to SPPG, at present in Singapore, the communication protocol of the smart meter project is based on RF mesh networks, 4G data transmission and fibre optical network as an upstream backbone of the network. Though many utilities in the world choose to deploy LPWAN technology to implement point-multipoint solutions, they still use cellular connectivity for backhauling the regional data to a central management system. Older cellular standards such as 2G/3G are cost effective and provide ample data speeds of 0.1-42 megabits per second, however they do not provide low power solutions for utility meters. Moreover, their infrastructure is rapidly overtaken by other technologies such as 4G/5G as networks evolve. Longevity is a serious concern since, in countries like Singapore and North America, 2G is no longer available.

LPWANs technologies such as Sigfox, Lora and NB-IoT are more popular for IoT due to their low cost, durability and wide-range connectivity based on mobile technology. UnaBiz, a Sigfox network operator (partnering with SK Telecom), has recently announced its official

launch of LPWAN in Singapore [5]. In Europe, the Sigfox operators sell IoT network connectivity for as low as US\$1.00 per device per year whereas in Singapore UnaBiz has even offering prices as low as S\$1.00 per device per year to the highest tariff being S\$12 per device per year [6]. The cellular connectivity standard 5G has now embraced the NB-IoT and LTE-M technologies and by upgrading to 5G, the utilities future-proof their solutions, thus delaying the need for upgrading as long as possible [7].

Smart protective relays

For the case of protection systems, IoT technologies will be necessary for IEDs (Intelligent Electronic Devices, usually connected using LAN), smart relay sensors, and agent-based protection systems. The main features of a IoT-based protection system include: a) advanced and adaptive protection algorithm, b) data acquisition from different locations of the power grid, c) real-time monitoring and real-time notifications of fault events, and d) flexible and scalable communication infrastructure with convenient interfaces through Web-based protocols and services. With standard IEC 61850 communication protocols commonly accepted, agent-based adaptive protection schemes in real-world applications will become more and more prevalent. Agents that can protect itself against malicious attacks and are capable of self-healing are discussed in [8]- [10] for power system protection with renewables.

The overall IoT cost mainly depends on technology, data rate, routing, energy efficiency, security. For example, the rule of thumb is that if a smart meter costs about \$100, it will require about \$300 in additional costs such as routers, repeaters, network planning, field installation, etc. for a total installed cost of about \$400 including some years of data plan.

Add-2.2.3 Cybersecurity considerations for PV grid integration

The integration of PV energy sources in power grids and its associated technologies such as distributed generation and storage is transforming power grids worldwide. One of the key functional components for integrating PV energy sources is information and communication technology (ICT) that enables the distributed energy resources to reach to market prices, and provide configurable grid-support in coordination with aggregators and utility control systems [11]. The use of communication and networking technologies also allows the owners of PV sources, the utility system operators and equipment manufacturers to control the devices in real-time, for example, to provide critical reliability services such as frequency and voltage regulation [11]. The measurement data and control signals that underpin the operation and integration of such PV distributed energy resources will be carried over public communication infrastructures such as the Internet. Consequently, the cyber-security of the network, command and control centre, data repositories and the PV devices form a critical factor in the overall reliability of the power grid. Large scale integration of PV energy sources in power grids thus have to consider the possibility of cyber-security vulnerabilities and threats, their potential for compromising critical reliability services, and the response and recovery in case a threat event occurs.

A roadmap describing the process of providing and improving the cyber-security for PV integrated power grids over the next five years is shown in Figure Add-2.8 [11]. PV system cyber security is a sub-set of the larger domain of Industrial Control System (ICS) and energy cybersecurity, and the best practices of the constituent communities can be broken into two thrusts: stakeholder engagement and cyber-security research and development (R&D). For engaging stakeholders, activities such as workshops to establish public-private partnerships, formation of working groups, educational activities, and incident planning and response should be undertaken. The R&D thrust focuses on new research on cyber security for securing PV components, taking into account the specific characteristics and features that are introduced by the PV systems. The stakeholder engagement and R&D efforts together should lead to new cyber security requirements and also aim at developing new technologies and standards that can be adopted by the industry.

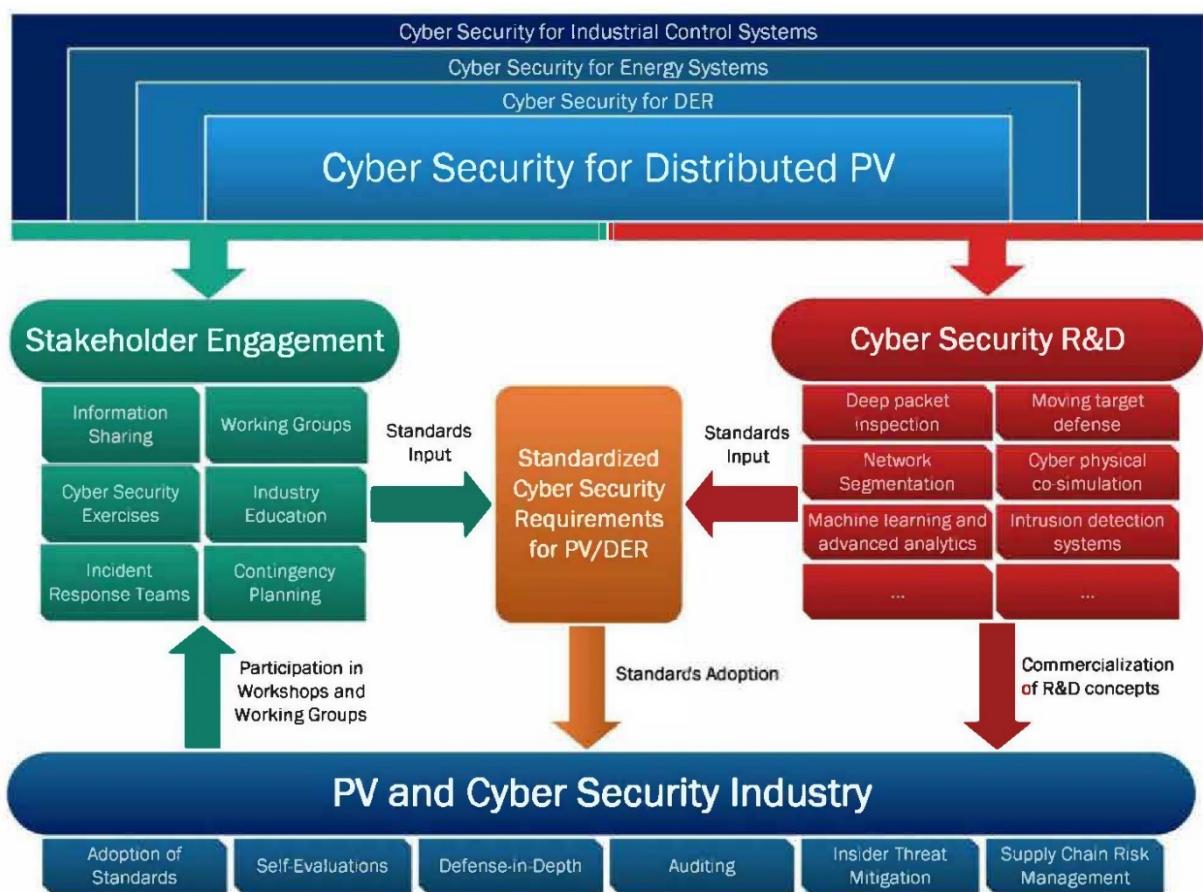


Figure Add-2.8: Process for achieving cyber security of PV systems [11]

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