International Review of Residential PV Feed-in Management

A Review of Technologies, Practices, and Applications

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ABSTRACT

The Australian Energy Market Operator (AEMO) is investigating technological and functional solutions to the challenge of integrating large amounts of distributed, residential-scale photovoltaic (PV) generation. Information is provided on the following five key elements necessary to perform management of PV feed-in: device hardware, communication protocols, network infrastructure, a management system, and interconnection agreements. EPRI conducted interviews with representatives from entities facing similar challenges, including from the United States, Germany, Japan, and parts of Australia outside of the National Electricity Market and South West Interconnected System. The interviews and research revealed similar efforts to AEMO, yet none in widespread use that simultaneously address all three challenges of 1) high PV penetrations, 2) consisting mostly of small, distributed PV systems, and 3) on systems without strong (or any) interconnections to neighboring countries or regions. In considering solutions, a holistic view of PV management that includes more than just feed-in management (e.g. other advanced inverter functionalities and customer control of their net energy output) is likely on the horizon.

Keywords
PV Feed-in Management
Distributed Energy Resources
DER Management System

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PRIMARY AUDIENCE: Australian Energy Market Operator Limited (AEMO) technical staff

SECONDARY AUDIENCE: AEMO non-technical staff, Australian National Electricity market industry stakeholders, Australian Energy Market Commission, Australian Government

KEY RESEARCH QUESTION

Australia is among the world leaders in PV penetrations with capacity continuing to increase. Unlike some other countries in this circumstance, however, Australia's PV is mostly distributed residential systems. For this reason, AEMO is trying to assess PV feed-in management options as a means of accommodating more of this distributed solar generation by learning what has been done elsewhere around the world. This research is aimed at reviewing technologies & practices at the device, protocol, network, management system, and interconnection agreement levels that can inform best practices. It will also investigate what is being done in those five areas to deal with similar PV-related issues around the world.

RESEARCH OVERVIEW

At the request of AEMO, EPRI set up and conducted interviews with various entities experiencing similar issues, compiled and confirmed the interview notes with interviewees, and then combined these findings with internal knowledge/expertise and external sources into this summary report. During the data gathering stage, EPRI also provided AEMO with periodic webcast-based updates, summaries of data gathered, and deep technical dives into topics such as network protocols or distributed energy resource management systems. When mutually agreeable, EPRI connected AEMO with utility contacts for further discussion.

KEY FINDINGS

- Given its current levels of PV generation, a high percentage of which is residential rooftop systems, Australia is one of a few countries that face the need for small-scale PV feed-in management, a scenario arising earlier than most.
- Five elements are necessary to establish feed-in management capabilities: device functionality, a communication protocol, a network architecture, a management system, and an interconnection agreement.
- In all aspects of PV (or any distributed energy resource) management, standardization is critical to efficient system implementation.

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- PV feed-in management has been demonstrated at scale by both distribution and transmission operators; however, early examples have been dedicated systems for real power management only. Emerging solutions are combining feed-in management with other functionality such as voltage or frequency regulation.
- With increasing penetration and expanding requirements for customer-generators comes a need for more advanced device features, communication protocols, networks, and policies.

CASE STUDIES IN FOCUS

The following case studies were investigated for their relevance to feed-in management of residential-scale PV:

- Hawaiian Electric – feed-in management of new systems using disconnect switch in production-type revenue meters
- Japan – multiple pilot projects testing curtailment of PV using internet communication pathways
- Germany – curtailment option for new residential-scale PV installations using one-way radio ripple control
- Horizon Power – multiple pilot projects managing PV feed-in within isolated microgrids (largely over cellular); also investigating control through an internet-based distributed energy resource management system (DERMS) and use of a third-party aggregator
- Energy Queensland - Lockhart River Pilot project on a standalone microgrid investigating automated control of four PV systems using a programmable logic controller over ultra-high frequency (UHF) radio links to respond to dynamic limits at the central diesel generating station
- Arizona Public Service – pilot project involving 1,600 utility-owned residential PV inverters to demonstrate management of real and reactive power functionalities

WHY THIS MATTERS

Understanding the requirements, available options, and the distinctions between implemented solutions can help to inform future PV feed-in management implementation strategies. Additionally, the compiled case-studies allow for investigation of what worked well and which aspects or strategies could be revised. The culmination of both sources of information enables utilities and governing agencies to potentially avoid costly and ineffective/inapplicable solutions in favor of more effective ones.

HOW TO APPLY RESULTS

The collection of information contained in this document can be used to inform decisions concerning how to implement PV feed-in management. Solutions presented herein that extend beyond that capability could simultaneously be given consideration so that the design choices for feed-in management could be deployed alongside a broader refresh of DER and advanced inverter capabilities.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Significant work related to DER management systems is ongoing at EPRI (in the DER Integration research area) and may be of interest.
- Similarly, research related to the protocols and communication for DER (such as this report on the "Value of Direct Access to Connected Devices") will help to inform design considerations. (This work is ongoing in EPRI's Information, Communication, and Cyber Security (ICCS) research area)
- Continued discourse with utility and agency partners facing similar issues may help to further refine and define best practices.

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PROGRAM: Integration of Distributed Energy Resources, P174

ACRONYMS

AEMO – Australian Energy Market Operator

AMI – advanced metering infrastructure

API – application program interface (software)

AS/NZS 4755 – Australian/New Zealand Standard - Demand Response Capabilities and Supporting Technologies for Electrical Products

AS/NZS 4777 – Australian/New Zealand Standard - Grid Connection of Energy Systems via Inverters

DER – distributed energy resource(s)

DERMS – DER management system

DNP3 – Distributed Network Protocol

DNP3-SA - Distributed Network Protocol Secure Authentication

DRED – demand response enabling device

DRMS – demand response management system

HEMS – home energy management system

IEC 61850 – International Electrotechnical Commission standard on communication networks and systems in substations

IEEE 1547 – Institute of Electrical and Electronics Engineers Standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces

IEEE 2030.5 – Institute of Electrical and Electronics Engineers approved draft standard for smart energy profile application protocol

MPLS – multiprotocol label switching (or multiple protocol label switching)

OpenADR – Open Automated Demand Response

PLC – programmable logic controller

PV – photovoltaic; used in this report to broadly mean photovoltaic solar panels and the associated hardware that connects them to the grid

RPA – reference point of applicability

SCADA – supervisory control and data acquisition

UHF – ultra high frequency (radio communications)

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

Balancing generation and demand is critical to the operation of a power system. To maintain this balance, the ability to dispatch resources is required. As PV becomes an increasingly significant generation resource, management of PV feed-in may likewise be necessary to maintain power balance. Without management capability, additional PV generation may be prevented from interconnecting or forced to pay for costly distribution/transmission network upgrades. Many places in the world may eventually face this condition as PV penetrations increase, but Australia is facing it sooner, being among the leaders in total PV adoption (Figure 1). Countries such as Belgium and Italy currently surpass Australia in total PV penetration, but unlike Australia, these and other European countries share multiple interconnections with neighboring countries, potentially enabling export of excess PV generation.

If PV feed-in management must be performed, managing power output of large-scale PV generators has typically been the more cost effective choice. Eventually, this need may extend to small-scale PV as well. Since residential PV[1] constitutes most of Australia's PV capacity (Figure 1), Australia may need to add management and control of this smaller-scale, rooftop PV to its portfolio of PV management capabilities earlier than most other jurisdictions. It is for this reason that the Australian Energy Market Operator (AEMO) is investigating technological, procedural, and other solutions to this challenge. The contents of this report are a collection of some of the leading small-scale PV management examples from around the world.

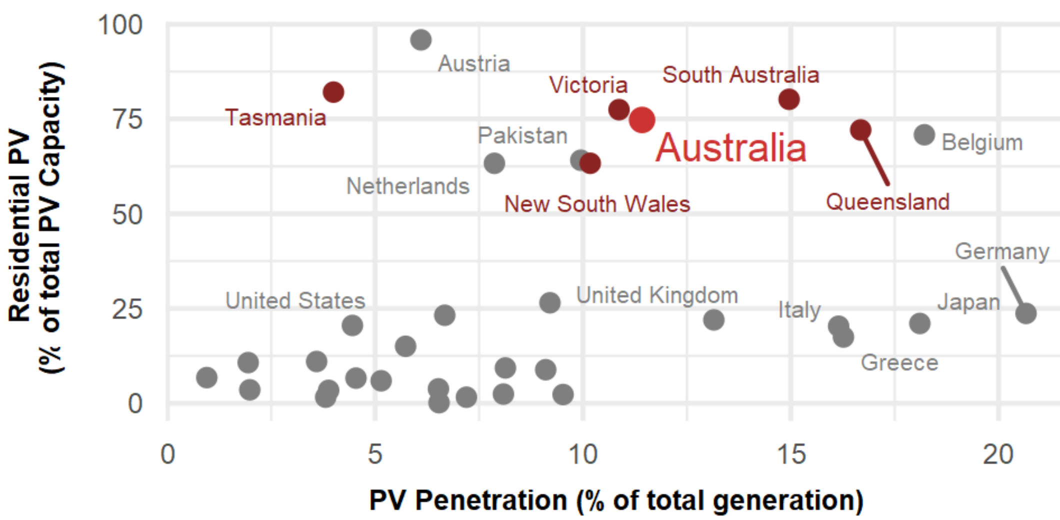

Figure 1
Total PV capacity as percentage of total generation capacity (all kinds) and percentage of PV that is residential-scale. Data courtesy of Bloomberg and the Australian PV Institute.

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[1] In the context of Figure 1, "Residential PV" refers to systems rated at 10 kW or less as this was the data available. In the remainder of this report, residential or small-scale systems typically refers to PV installations with a rating of 30 kW or less.

Case Studies in Focus

The following case studies (Table 1) were investigated for their relevance to feed-in management of residential-scale PV:

Table 1
Summary of case study attributes, management method, and operational/usage status.

Entity	Deployment Type	Drivers	Management Method	Is System Operational/Utilized?
Hawaiian Electric	System-wide for all new customer-owned PV	High PV penetrations on isolated grids, trouble balancing generation & load	Disconnect switch in production-type revenue meters	Implemented broadly, but have yet to call for a broad curtailment event from small-scale PV.
Japan	Multiple pilot projects	Aggressive renewable energy targets, favorable 2012 PV feed-in tariff, localized power surpluses & voltage violations	Utility DERMS sends curtailment command to devices/HEMS over internet communication pathways	Small-scale PV has only been curtailed in demonstrations or pilots.
Germany	System-wide for all new customer-owned PV	World's highest percentage of PV generation capacity	Curtailment option for new residential-scale PV installations using one-way radio ripple control	Implemented broadly, but have yet to call for a broad curtailment event from small-scale PV.
Horizon Power	Multiple pilot projects	Witnessing dramatic effects from passing clouds, PV capacity limit reached in some areas	PLC sends commands to inverters. Investigating PV management via DERMS and a third-party aggregator	Systems are currently being utilized in isolated network projects, including the current Carnarvon trials
Energy Queensland	Small demonstration project (four PV systems)	Small, isolated microgrids with PV capacity in excess of minimum load	PLC sends commands to the larger PV inverters	Demonstration is operational and routinely utilized, but only on an isolated microgrid.
Arizona Public Service	Large-scale pilot project (1600 inverters)	Routine reverse power flow (back to transmission) on research feeders, anticipated region-wide increases in installed PV capacity	Human-designed commands sent to PV inverters over cellular modems	Demonstration has been operational since 2016. PV power limit has been demonstrated (as have additional PV management tests such as reactive power functions), but for test purposes only.

2
REQUIREMENTS FOR CURTAILING PV GENERATION

To communicate with and potentially curtail distributed PV generation, the following five key elements are needed:

1. Devices at the customer-level that can carry out the curtailment command[2]
2. An agreed upon protocol to facilitate communication
3. Network infrastructure to maintain connectivity between the operator and device
4. A management system to calculate, distribute, and verify responses to the curtailment command
5. An arrangement allowing system operators to manage customer-owned PV (customer contract/agreement)

The above elements are presented graphically in Figure 2.

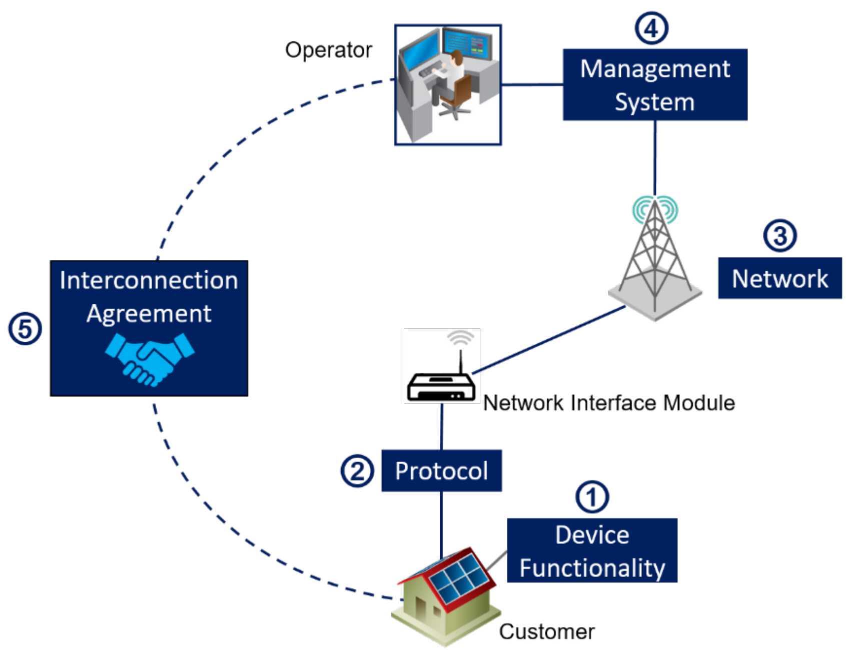

Figure 2
Graphical depiction of the key elements involved in management of distributed PV systems.

Customer-Level Device Functionality

Curtailing PV generation requires hardware and software for on-site controls to either disable, reduce, or absorb PV generation. Each approach requires a different technological solution. Temporary cessation of a PV generator's output can be accomplished simply by disconnecting

[2] Control devices are not limited to switches, inverters, or dedicated controllers. More general-purpose controllers that control multiple end devices such as home energy management systems (HEMSs) could also fulfill this need.

the system with a switch.[3] The same can usually be done with proper inverter controls, with the added benefit that partial reductions are often available as well. With controllable local load or battery storage, residential PV production may be absorbed by increasing load demand or charging storage. Such self-consumption could reduce the net output to the same desired level without the need for PV curtailment. A more detailed look at each approach follows:

1. **External disconnect switch –** As the most simplistic control implementation, PV inverters are simply disconnected from the electric grid by means of a remotely controlled external switch. The solution is simple and allows for retrofitting, but often requires a separate disconnect switch, control hardware, and sometimes separate metering so that customer load remains connected when PV is taken offline. The additional hardware adds costs to the PV system without enabling any additional functionality beyond disconnection and reconnection of the PV. Complete disconnection also results in losing 100% of the energy from affected systems (assuming no storage) [4], with extra energy being dissipated as heat in the solar modules. The inverter disconnect switch is the current solution used in Hawaii, primarily for its simplicity and universal compatibility. In this case, they were able to use the disconnect capability of the PV AMI meter (aka smart meter) to act as the disconnect switch.

2. **Inverter-controlled power output –** Most inverters are not only capable of complete power cessation/restoration (effecting the same change as a disconnect switch), but are also capable of granular reductions in power output. Standards such as IEC 61850-7-420 reference both connect/disconnect and power limiting functions, and standards like IEEE 1547-2018 (Sec. 4.6) require both of these control capabilities from DER.[5] Power

Additional Inverter Functions & Applications

Most modern inverters can perform a long list of grid support functions including voltage regulation with Volt-VAR, or frequency control ancillary services (FCAS) with a frequency-Watt function, among others. Standards like AS/NZS 4777 are requiring that these capabilities be available on all new PV systems. While many auxiliary inverter functions can run autonomously, utility communication and control can allow for more capabilities than just curtailment. Possibilities include:

- Settings updates to active functions (seasonally or as needed)
- Enabling and disabling of certain functions
- On-command dispatch of reactive power additional to active power
- Self-reported values for increased visibility

Some utilities are already implementing subsets of these capabilities to regulate local voltage levels, increase hosting capacity, and provide other grid services. See Germany, Horizon Power, and Arizona Public Service case studies.

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[3] An example of this is Demand Response Mode Zero (DRM0) in AS/NZS 4777, where a signal either directly to the inverter or to an external device results in the inverter's disconnection from the network.

[4] If a battery energy storage unit is present, consideration must be given as to whether it should disconnect with the PV (to allow it to absorb local PV generation) or remain connected to the grid (to allow grid-supplied energy excesses to be absorbed).

[5] More advanced functions requiring autonomous action on the part of the inverter (e.g. Volt-Watt or Frequency-Watt) are also outlined in standards such as IEEE 1547. More information on these and other functions may be found here: Common Functions for Smart Inverters: 4th Edition. EPRI, Palo Alto, CA: 2016. 3002008217.

reductions are typically inverter responses to a commanded maximum limit as in Figure 3 rather than a fixed-power dispatch (e.g. reduce power by 2 kW). Control of output power using the inverter is unlikely to incur additional power hardware costs, although additional communication hardware may still be necessary. The magnitude of lost energy will vary based on the depth of curtailment, but is generally less than the external disconnect case. This partial power limiting has been physically demonstrated in Japan, Australia, Germany, and Arizona, though it is sometimes implemented with coarse increments (e.g. 0%, 30%, 60%, or 100% options in Germany).

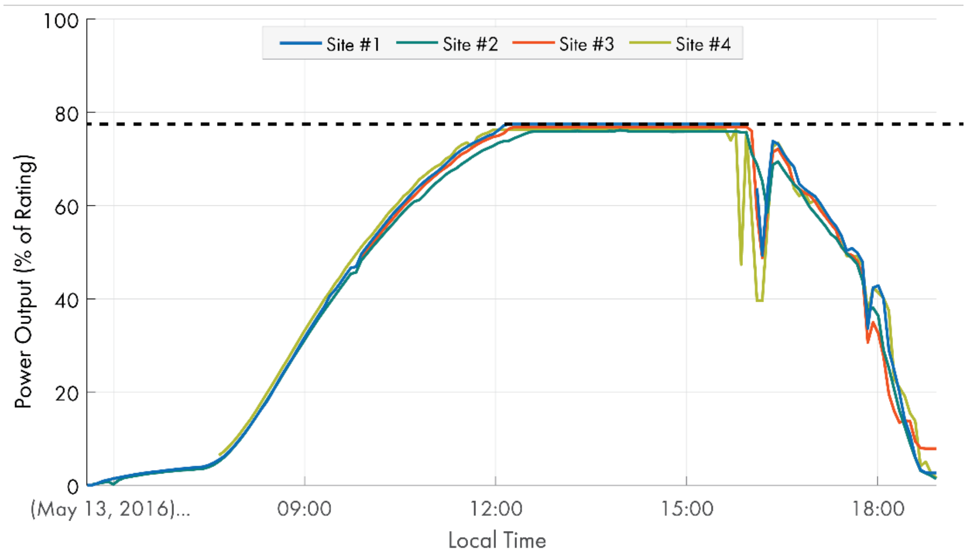

Figure 3
Field test results of inverters obeying a commanded 75% maximum export limit in Arizona, USA

3. **Onsite energy management (site control)** – To minimize lost energy during curtailment, PV inverters can be coupled with energy storage, controllable loads, local energy management systems, and/or demand response enabling devices (DREDs) to reduce or eliminate net exports. For this reason, the IEEE 1547 standard uses the term 'reference point of applicability' (RPA) to allow for flexibility in where interconnection and interoperability requirements are to be met (beyond just the terminals of a PV inverter). Combined PV and storage systems are becoming more popular in Germany and Hawaii, as are programs that incentivize self-consumption. However, energy storage often adds significant hardware costs, systems can vary significantly in topology (e.g. AC- versus DC-connected PV and storage), and the required controls lack broad standardization internationally.[6]

PV curtailment can be accomplished relatively simply today by means of PV disconnect switches or direct control of inverter output. However, customers are increasingly interested in home energy management systems, leading to more opportunities for onsite energy management during curtailment periods. In Hawaii, for example, new PV systems can connect under the Smart Export Program, which allows for unlimited export, but without receiving credit at mid-

[6] AS/NZS 4755 has standardized the demand response of energy storage; however, the industry is still fragmented on communication standards between the utility and the device.

day. This leads to a financial incentive for customers to either store excess energy or self-consume.

Protocol

The protocol[7] is the agreed upon method which monitoring and control signals are transferred between two entities, in this case, the grid operator (or aggregator) and the end device. Often, messages of any protocol are embedded or "wrapped" in a transport layer to pass through a network, but the protocol itself dictates the syntax or structure of the message itself once it is "unwrapped" at a network interface module (see Figure 2). For feed-in management, the protocol must communicate the beginning and end of the curtailment period and the depth of the curtailment (including disconnection if necessary).

Communications protocols can be either designed by an independent entity (proprietary[8]) or agreed upon by a consensus process (open). Allowing each manufacturer/aggregator/etc. to design their own protocol has advantage and disadvantages compared to using open protocols. These are outlined in Table 2.

Table 2
Advantages and disadvantages of proprietary versus open protocols

	Proprietary Protocols	Open Standard Protocols
Advantages	• Allows for optimization to their hardware or communication network, reducing the potential for unused elements and unnecessary overhead • Allows the protocol to adapt quickly to changing market needs or advanced functionality	• Allows interoperability between vendor systems without prior knowledge of each other's systems • Allows for reduced custom coding and cost with each system that is integrated • Often have measures in place to prevent churn (rapid updates) to protocol to provide stability to users
Disadvantages	• Risks additional implementation and maintenance costs and time if multiple vendors must be interfaced to a single utility at either the equipment, network, or aggregator levels – number of different vendors and devices is likely to increase with time. • Risks vendor lock-in and potential "rip and replace" if the technology or aggregator becomes defunct	• Risks slower adaptation to new technologies or system conditions because of updating processes and associated review periods inherent to open protocols • Risks additional overhead to support communication elements that are not necessary for a specific end-device

[7] This includes the communication protocol and the information model (both defined in glossary). Protocols such as IEEE 1815 (DNP3), IEEE 2030.5, IEC-61850, and SunSpec Modbus, are all different communication protocols that reference the same information model (IEC 61850-7-420).

[8] An example of a single-entity controlled protocol could be a vendor who has developed their own communication protocol for exchanging information between their control center and their product. This may be available to anyone to use, licensed at a cost, or secret. It may or may not have an associated information/semantic model.

Cybersecurity Risks

When a utility or aggregator has connectivity to distributed resources, cyber security is necessary to:

- Prevent access to the rest of the utility network from unauthorized users
- Limit access to customer equipment to prevent tampering
- Ensure data integrity so that reported measurements may be trusted to inform operational decisions

Network security naturally becomes more difficult (and important) as the number of customer devices increases and the inverters are increasingly relied upon for managing the grid.

Older, low-complexity protocols do not natively support core security functionality such as authentication or encryption. These must be added separately, which increases cost. High complexity protocols offer more built-in security features, but may require additional data transfer and computing power from customer devices to decrypt instructions and encrypt their response.

At present, protocols used for communication with DER do not contain inherent security features and cannot verify the origin of communications. In the short term, protocols like DNP3 SA build security features on top of a modified DNP3 protocols. In the long term, new protocols such as SSP-21 are being designed from the ground up with security features in mind.

Early implementations of curtailment (or other smart PV functions) have largely been either over proprietary protocols (whether published or not). Interfacing with these devices has required the management system to implement the protocol that is supported by each end device individually. This has added considerably to development times and costs for implementations at Energy Queensland and Arizona Public Service, for instance. In contrast, the use of open protocols can reduce the number of protocols that must be supported and allow a variety of models to connect without having to make updates to the management system each time a new model or manufacturer is introduced.[9] In the USA, the presence of one of three open protocols (DNP3, IEEE 2030.5, and SunSpec Modbus) is mandated through IEEE 1547-2018.[10] California took this one step further and restricts implementation to only the 2030.5 standard in its Rule 21[11].

The other aspect of the protocol to consider is the complexity or the "weight" of the protocol. More complex protocols allow for certain advantages (such as cybersecurity), however, may add burden to the communication system, requiring more bandwidth and throughput from the network.

There are several choices of protocol complexity outlined in Table 3:

[9] The Value of Direct Access to Connected Devices – 3002007825 - https://www.epri.com/#/pages/product/000000003002007825/?lang=en

[10] IEEE Standard 1547™ — Communications and Interoperability: New Requirements Mandate Open Communications Interface and Interoperability for Distributed Energy Resources – 3002011591

[11] California's electric Rule 21 describes the interconnection, operating, and metering requirements for generation facilities to be connected to a utility's network. Further information may be found at www.cpuc.ca.gov/Rule21/

Table 3
Overview of communication protocol levels of complexity

Complexity	Benefits/Shortcomings	Examples
Low Complexity – with data transferred measured in "bits", these protocols barely carry more information than an address for the recipient group and the amount of curtailment.	• Completely dependent on the end device to determine the meaning of a string of bits • Do not typically receive feedback from the device • No support for modern routing of signals or cybersecurity • Typically used with low-bandwidth networks such as long-wave radio or low-frequency power-line carrier	• Versacom[12] • Swistra
Moderate complexity – data transferred measured in "bytes", these protocols support more complex signals and modern routing (such as Internet Protocol, or IP)	• Rely on a predetermined set of "registers" or "inputs" that the end-device interprets the meaning of the value stored in each location[13] • Information is then transferred between devices by a series of "reads" and "writes"	• Modbus • Distributed Network Protocol (DNP3)
High complexity – data transferred measured in "kilobytes," these protocols resemble internet traffic, and in many cases reuse components of the internet's architecture (and appear similar to XML)	• Shares established cybersecurity components from other systems • Data transfer is significant for each message, including simple commands	• IEEE 2030.5 • OpenADR

Ultimately, managing PV feed-in is one of the simplest commands required of a smart inverter since communication is infrequent and likely contains simple messages. The complexity of the protocol required will likely be determined by other, more demanding applications (such as DER visibility, distribution optimization, and other uses where more data is exchanged more frequently) as well as networking and cybersecurity requirements. Utilities like Salt River Project in Arizona, USA are investigating the capabilities of AMI, SCADA, and cellular networks to see which will fit their needs. Similarly, PPL Electric Utilities in Pennsylvania, USA are investigating what modes of control can be used over their AMI network.

In a perfect world, utilities would be able to select protocols and communication networks freely to match their application however near-term solutions often require the use of existing systems. Most examples of smart inverter curtailment use protocols already in use for managing customer resources (such as demand response) or distribution system resources because of time or cost restrictions. For instance, Versacom (ripple control) was already being used for demand response in Germany before being applied to PV feed-in management, and likewise, OpenADR was being

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[12] The Versacom protocol has been used in curtailment applications in Germany. It communicates over long-wave radio and is thus sometimes associated with the term 'radio ripple control'. Many more utilities, including Energy Queensland, make use of ripple control via powerlines for demand response.

[13] Interoperability using these moderate complexity protocols requires an agreed-upon mapping among inverter and control system vendors.

used in Japan for demand response before being implemented in PV management pilots. For longer-term applications, it is important to consider other protocols where appropriate.

Network Infrastructure:

There are several options for carrying the curtailment signal from the grid operator to the customer premise.[14] The preferred method will typically be selected by the availability of existing infrastructure, required reliability and security needs, tolerance for added cost, and the complexity of the additional requirements for the PV system. Options include:

- **Radio –** using traditional radio transmission bands (such as long-wave or UHF) to transmit signals (typically one-way). Communication is typically very low bandwidth. Signals are "broadcast" so that all receivers listen to the signal, however the transmissions may be "keyed" so that only certain units respond. The advantage is the ability to control a large number of systems quickly and at low recurring costs, however, unidirectional communication does not provide an easy method for verifying that the command has been executed. In terms of security, anyone can record and broadcast radio transmissions (albeit usually over short ranges), so encryption of signals or even just encryption of authentication keys could reduce the possibility of fake commands being obeyed.

- **Power Line Carrier** – transmitters use the power line as a medium for communication with many receivers by placing a "tone" along the line at a higher or lower frequency than the normal frequency of the grid.[15] Communication is also very low bandwidth and the tone generator can be costly. Advantages include very low recurring costs and no dependence on outside systems, but signals may be prone to interference and may not transition well (or at all) across domains (from transmission to distribution).[16] The downsides in implementation act as benefits in terms of security. Creation of signals is difficult without expensive equipment, and locally-generated signals are unlikely to influence nearby houses after passing through a transformer. These two characteristics make Power Line Carrier signals difficult to forge and inherently more secure.

- **Advanced Metering Infrastructure (AMI)** – utilities often deploy a mesh network of nodes and collectors near customer sites, as well as backhaul to the central utility system. Typically deployed for billing purposes, these networks may be also used for operational purposes. Examples include using the meter itself as a disconnect (Hawaii) or connecting the inverter itself to the network through a gateway. Advantages are security and low recurring costs, however, the network bandwidth may be limited compared to cellular or customer internet. In terms of security, AMI mesh networks are usually equipped with security capabilities by design. The most prominent vulnerability is that such security

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[14] It is possible to use a more advanced protocol between the utility and some sort of local controller (DERMS, HEMS, etc.), and then have that controller use a simpler protocol between it and the inverter. Examples include home energy management systems (HEMSs) in Japan, as well as demand response enabling devices (DREDs) in Australia.

[15] Audio frequency load control (AFLC) or ripple control is one such form of this communication mode.

[16] The issue of domain transition may be addressed by using repeaters at substations.

measures as encryption may not always be enabled by default. Without the network protection capabilities enabled, insertion of an unwelcomed network node is not difficult.

- **Cellular** – each site is given an independent connection to a shared wireless network. Characterized by broadband speeds and metered data (cost per kB). Advantages include reliability and low upfront cost, with the challenges of higher recurring costs depending on the amount of data transfer required. Multiple security layers are available for cellular communications, and cellular-connected devices can be set up with IP address routing so that they are only visible/accessible from utility networks.

- **Public (optionally, Privatized) Internet** – uses the customer's normal broadband connection for data transfer. Typically, the data traffic is not metered, however, the connection is shared with many other forms of data traffic. Devices may use a virtual private network (VPN) to secure communications with some configuration. Advantages include a very low up-front and recurring cost provided that the customer already has broadband at the site. However, reliability (at the customer or network-level) as well as security are typically major concerns. Like cellular, multiple types of security can be wrapped around Internet traffic. Additionally, multiprotocol label switching (MPLS) is a type of VPN that is partitioned off from the public internet. This feature makes it advantageous from a security standpoint, but its expense means that it is likely only to be used to communicate with a local transmitter, not directly to each home or device.

One of the most critical elements is matching the network capabilities to the protocol and application requirements during the design stage (Table 4). Some high-level considerations are as follows:

- Low-bandwidth or metered connections may not be good fits for very complex protocols as the limited bandwidth could result in delays.

- Protocols that lack good procedures for routing or security over IP-networks should not be considered for cellular or Internet applications that are designed for those purposes.

- Bandwidth capabilities of cellular and Internet pathways may be excessive for some applications (e.g. simpler protocols or infrequent commands), needlessly increasing costs (especially in the case of cellular).

- Certain communication networks are more conducive to message broadcasting (single 'speaker', many 'listeners') such as narrow-band radio. Others, that sequentially address each end device, (e.g. private internet), may take longer to convey a message to a large number of devices.

- Even low-bandwidth protocols used in very demanding, high-traffic applications (e.g. large numbers of devices and/or high rates of communication initiation) may stress networks.

- Therefore, it is important to evaluate not only the protocol selection but also the intended near-term and long-term applications such as system monitoring or distribution voltage regulation using smart inverters.

Table 4
Generally appropriate network structures for protocols of varying complexity.

Communication Medium Examples	Low Complexity (Bitwise protocol)	Medium Complexity (DNP3, SunSpec, etc)	High Complexity (IEEE 2030.5, OpenADR)
Narrow-band Radio (UHF)	✓		
Power Line Carrier	✓		
Advanced Metering Infrastructure		✓	
Cellular		✓	✓
Private Internet (VPN)		✓	✓
Public Internet			✓

Management System

When managing PV feed-in, the management system issues commands directly or indirectly to PV systems in order to reduce (or restore) their net output.

Today, PV feed-in management typically involves a system operator (either human or electronic) whose command is repeated and distributed to all PV systems, either directly or via an aggregator. The control entity decides what signals are sent, verifies the response, and takes any additional action necessary. In Germany, a human distribution system operator issues a command for a discrete curtailment percentage (typically 0%, 30%, 60% or 100% via a radio ripple control center operator. The command is then broadcast over long-wave radio to all PV systems equipped with a receiver. In Energy Queensland's Lockhart River demonstration, an electronic programmable logic controller (PLC) makes these decisions in place of a human operator. Requested curtailment is dynamic in the case of the PLC since human intervention is not necessary. Both systems mentioned here are only designed and used for feed-in management right now and may not be suited to handle other inverter functions.

It is expected that these single-purpose systems will give way to more advanced distributed energy resource management systems (DERMS). Consider, for example, the move to a DERMS in Japan after having first used a centralized dispatch server for management of PV in their pilot projects[17]. Many other utilities have likewise announced projects implementing DERMS including Los Angeles Department of Water and Power, Pacific Gas and Electric, and Tucson Electric Power. Such systems communicate with multiple device types, potentially using different protocols, and are designed to optimize subordinate resources while providing a single point of contact for operators. DERMS systems can curtail or restore resources based on specific characteristics such as technology type, location, or rated power, and can also report back the status and capabilities of DER or other DERMS under its control. The management systems may represent a significant increase in cost and complexity of PV (or DER) control, but they allow for more customized and targeted operations as well as more advanced functionality beyond just feed-in management.

Third party aggregators may act in a similar manner to a DERMS, controlling an aggregated collection of resources that appear to the operator as a single resource. Aggregators may also be sent commands by a utility DERMS or use DERMS themselves to aggregate systems under their control. Horizon Power, for instance, has built an application program interface (API) so that third-party vendors could integrate with a utility DERMS.

Interconnection Agreement

If residential PV-feed in is to be managed, some type of contractual framework is typically in place between the managing entity and the customer. This enables the grid operator or a third-party to issue the curtailment command (or retract a permission-to-export signal) for some period of time[18].

Third-party Aggregators

Aggregators are non-utility companies that provide grid services through the collective control of numerous distributed energy resources. Use of third-party aggregators has multiple pros and cons.

Advantages:

- Reduces the number of end-points that utilities need to address
- Utility is not responsible for the protocol used between the controller and end devices
- Aggregators may provide more customer-friendly equipment, user interfaces, and customer service
- Potential for increased customer choice and greater access to different markets
- Aggregator assumes responsibility for distributing compensation (if applicable)

Disadvantages:

- Requires coordination and an additional interface, likely distinct from any existing device-level control
- Grid security vulnerability introduced by granting vendors access to potentially large quantities of generation
- Potentially precludes energy management at a customer level (e.g. if aggregator only aggregated PV or batteries not homes or sites)
- Potentially reduced visibility into the response of individual devices
- Possibility that aggregator goes defunct

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[17] Maeda, Ryo, et al. "Expectation for Smart Inverter & DERMS for Electric Power System Task." IEEJ Transactions on Power and Energy, vol. 138, no. 6, Jan. 2018, pp. 412–415., doi:10.1541/ieejpes.138.l6_1.

[18] There is variety in how lost communications are handled. For most deployed applications (including Germany and Hawaii) a loss of communications does not shut down the inverter. There are smaller pilots (such as Lockhart River) where the inverter must have communication with the system operator to be allowed to export energy.

Thus far, most of the agreements are limited in some fashion by either of the following:

- **Time** – managers are provided a limited number of hours of curtailment over some time period. One example is in Japan allowing 360 hours of curtailment per year.
- **Situation** – operators are allowed to curtail during "grid emergencies" for an undetermined number of events. However, the severity of the event, other options that were explored, and the amount of generation that was curtailed must be documented and reported to the regulator for each instance (Hawaii).

Monetary remuneration is not typically offered for "emergency" curtailment situations, though it may be offered if curtailment orders are issued for "economic" reasons.[19]

Most feed-in management arrangements thus far have focused on the generator itself, even though many utilities already consider (and meter) the net import or export of entire facilities. Limiting net export, particularly at the residential level, is a relatively new concept. Hawaiian Electric offers a schedule-based "smart" export program without credit for exported generation during the midday period. South Australia Power Networks is considering a limitation by command that would allow the local operator to limit facility export when necessary. Further development in this area is expected with increasingly prevalent battery storage units and flexible loads.

In any case, the expectation of PV feed-in management and the program rules are often determined at the time of interconnection. This allows the customer to plan for periods of curtailment and design their system accordingly. Helping the customer to understand everything that is expected of an interconnected generator, and why PV management can be necessary, may help make this process easier.

Cost Considerations

Each of the five required elements (e.g. customer equipment or network deployment) has a unique cost structure considering the capabilities required, the amount of investment that can be shared with other use cases, and the methods used for implementation. Most pilot projects thus far have used existing hardware and network infrastructure in an attempt to control costs and accelerate deployment; however, expensive and bulky communication equipment and custom software significantly cut into any anticipated savings. Future implementations may experience less of these additional burdens as communications with PV generators (of varying sizes) becomes more common.

Some lessons from prior experiences may also aid in cost-effective implementation:

- Avoiding retrofit of customer equipment. Germany spent hundreds of millions of euros retrofitting thousands of individual PV systems to avoid the "50.2 Hz issue."[20] The

[19] In some places, agreement to PV feed-in management could be compensated with or "traded" for an increase in permissible, installed power rating.

[20] Under previous regulations, all PV inverters were set to immediately disconnect if the grid frequency ever reached 50.2 Hertz. The "50.2 Hz issue" refers to a scenario where vast amounts of PV would disconnect simultaneously if the grid frequency ever reached this point, potentially destabilizing the rest of the grid.

majority of this cost was incurred sending technicians out to reprogram PV inverters with little or no additional hardware necessary. Avoiding this expenditure either by proactive requirement of the functionality or the ability to add functionality "over-the-air" without physical access is critical to controlling costs (though the latter introduces cybersecurity vulnerabilities).

- Using modularity to adapt to changing networks - Wireless communication networks have consistently had shorter lifespans than the 20-30 year lifespans expected of PV systems. Since “connected PV” is relatively modern[21], however, issues with sweeping communication upgrades or repairs have yet to present themselves. To avoid such a scenario, communication hardware at the customer should be modular so that the network portion could be replaced without having to replace the entire inverter due to a network change (such as moving from 4G to 5G wireless). This capability is already offered through the demand response enabled device (DRED) requirements outlined in AS 4755 and IEEE 1547 that specifies the interface to a communication module, but not the communication network type to be used.

[21] PV connected to communication networks has existed in utility-scale deployments for longer than residential-scale deployments where it has been relatively simple to replace the small number of communication devices.

3
CASE STUDIES

Only a few entities have begun to look seriously at residential PV feed-in management. Below are some case studies collected through interviews with leading organizations in this area.

Hawaiian Electric

Summary

The Hawaiian Electric companies have introduced PV curtailment into plans for new PV systems beginning in 2018. The plan is to use a dedicated PV production meter with a disconnect switch (that is installed with new PV system anyway) to remove PV capacity from the system during emergency conditions.

Motivation

Hawaii has seen very rapid PV growth since 2011, with cumulative installations across Oahu, Maui, and Hawai'i islands now totaling over 700 MW, or 21% of installed generating capacity (any type)[22]. Roughly 56% of this is residential capacity and is largely unmonitored and unmanaged by the system operator. Together with significant penetrations of wind generation (already being curtailed by around two percent[23]), matching supply and demand within small, mostly isolated balancing areas has become a challenge for Hawaiian Electric.[24] Programs allowing export (called grid-supply) are still the most popular options for new installations, particularly compared to the self-supply option.

Function

Hawaii's Rule 14H has required advanced inverter functions for PV systems installed since 2016 (an adapted version of California's Smart Inverter Working Group recommendations[25]). However, these requirements do not include externally-triggered PV export limiting by the

> **What about California?**
>
> The State of California is also a leader in PV adoption, having 16.2 GW of installed capacity (October 2017). Its Smart Inverter Working Group (SIWG) was also one of the first to standardize smart inverter behaviors, such as Volt-VAR control. The desired functionality from PV systems was divided into three phases:
>
> - Phase I – Autonomous Functions
> - Phase II – Communications
> - Phase III – Interactive Functions
>
> Since curtailment requires communications, it was placed in the "Phase III" category, and has not yet been required of PV systems.
> Large PV systems (that are transmission-connected) follow the normal bidding process for their generation, however, an agreement authorizing curtailment of smaller systems (particularly those "behind-the-meter") has not been put forward.

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[22] https://www.hawaiianelectric.com/about-us/power-facts

[23] https://www.hawaiianelectric.com/about-us/key-performance-metrics/renewable-energy

[24] Bird, Lori, et al. Wind and Solar Energy Curtailment: Experience and Practices in the United States, www.nrel.gov/publications. Technical Report NREL/TP-6A20-60983

[25] http://www.energy.ca.gov/electricity_analysis/rule21/documents/recommendations_and_test_plan_documents/Recommendations_for_updating_Technical_Requirements_for_Inverters_in_DER_2014-02-07-CPUC.pdf

inverter. Instead, Hawaiian Electric is planning to disconnect PV generators during grid emergencies via a disconnect switch in the PV system's dedicated production meter.

Protocol

The communication protocol will be proprietary to the AMI system, however, since the utility will own the AMI system, they have some ability to limit to a single vendor and/or protocol used.

Network

Communication to the production meters is planned over a cellular backhaul. If the customer lacks sufficient cellular signal strength, amplification or alternate communication methods are planned to be offered at the customer's cost. If communications are lost with the meter, the PV system will continue to operate without interruption. The long-term strategy is to integrate production meters through the field area mesh network, once the telecom infrastructure is built out.

Management System

Management of the curtailment signals is currently planned through the AMI vendor's software portal. If third-party alternatives begin to grow, integration with Hawaiian Electric's demand response management system (DRMS) could be an alternative strategy.

Interconnection Agreement

The ability to curtail (or disconnect) is provided through a new customer program[26] for behind-the-meter PV generation (up to 100kW) where exported energy is credited at a fixed rate regardless of time-of-day[27]. Periods of curtailment should coincide only with a grid emergency, and systems should not resume generating until after the event is cleared. No additional compensation is provided during curtailment periods. Quarterly, the utility is required to submit a summary of any events along with an estimate of curtailed capacity and a justification that includes the relevant system conditions that triggered the event.

Key Takeaway

Internal disconnect switches in Hawaiian Electric's AMI meters will be the primary means of curtailment until third-party vendors develop sufficient capabilities to manage PV feed-in during emergencies. This development could reduce direct utility costs and provide additional capabilities beyond curtailment.

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[26] https://www.hawaiianelectric.com/clean-energy-hawaii/producing-clean-energy/customer-renewable-programs/customer-grid-supply-plus

[27] Customers that are on the "smart export" rate, without credit for midday exported energy, do not have a communication or control requirement.

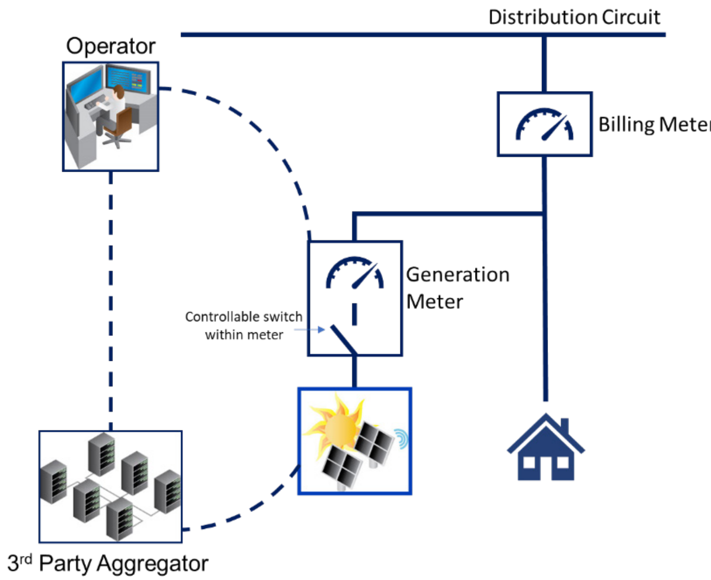

Figure 4
Diagram of control structure used for new residential PV systems in Hawaii

Japan

Summary

Japan has instituted aggressive renewable energy targets (22% of energy mix by 2030) that would likely require a PV generating capacity in excess of 64GW. In order to accommodate this increase, some Japanese utilities have instituted rules permitting connection of new PV generation under the conditions that 1.) The new PV plant can be curtailed for up to 360 hours per year and 2.) There is sufficient grid capacity for it the remainder of the year.[28]. Depending upon the region, different sizes of PV generators may be called upon to limit output, but effective January of 2015, all PV must be capable of receiving a dispatch signal. However, the system for generating, routing, and executing curtailment commands is still being developed.

Motivation

Japan has seen tremendous PV growth since the enactment of a PV Feed-in Tariff in 2012. Most of that growth has been in the small commercial market segment (50kW to 500kW), though residential PV has also doubled over that time period. Additional, approved PV (of all sizes) continues to loom. In 2015, it was reported that capacities of approved PV exceeded cumulatively installed capacities in most every region of Japan.[29] While average PV penetrations range from 2-8% in various regions of the country, Shikoku and Kyushu have witnessed max

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[28] Hiroyuki YAMADA, et al. National Survey Report of PV Power Applications in JAPAN 2017. International Energy Agency (IEA), 2018, www.iea-pvps.org/index.php?id=93&eID=dam_frontend_push&docID=4459.

[29] PV in Japan and Utility's Activities. RTS Corporation, 2015, PV in Japan and Utility's Activities, www.iea-pvps.org/.

solar penetrations of 56% and 61%, respectively.[30] During such periods, certain distribution networks have experienced a surplus of PV energy that results in voltage violations.

Functionality

Thus far, the inverter-level implementation of curtailment signals has been custom at each inverter.

Protocol

OpenADR has been adapted for use in demonstrations of PV curtailment in Japan. Existing pilots have used it as direct communication to PV systems as well as home energy management systems (HEMS). IEC 61850 is being explored as an additional method for large PV systems. Local protocols for small-scale PV systems may vary, and could include Echonet Lite or Sunspec Modbus. Implementation of IEC61850 protocols would be costly and complicated to implement, especially for smaller systems.

Network

Communication has largely been over the internet for these projects, with a mix of public and private (closed) networks. Signals are sent directly from the utility DERMS to inverters or to onsite energy management devices (such as a HEMS controller).

Management System

Initial demonstrations have incorporated an OpenADR server dedicated for processing PV curtailment commands (at the demonstration level). Future projects are considering curtailment as a part of a full-feature DERMS implementation. 3rd party aggregators may also be integrated through coordination with the utility DERMS.

Interconnection Agreement

Limited curtailment without compensation is required by law, up to 360 hours per year (after which point compensation is required). Seven utility companies are allowed to implement curtailment for residential and small commercial customers (less than 50kW) as of 2015. Curtailment of solar and wind is considered to be one of the last flexibility sources (just ahead of curtailing nuclear or geothermal power plants).

Germany

Summary

Germany, with its passage of the Renewable Energy Sources Act of 2012 (EEG 2012), now requests curtailment functionality from all PV generators greater than 30 kW, and as an option for PV generators less than 30 kW (alternative is to limit feed-in to 70% of rated capacity). The capability is only to be used during emergency periods and has thus far been secondary to curtailment of larger renewable sources, especially wind. Introduction of energy storage, new

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[30] Grid Integration with High PV Penetration: Approaches for the Japanese Situation. EPRI, Palo Alto, CA: 2017. 3002010000.

grid codes (as of 2018), and an upcoming AMI rollout offer opportunities for more flexible PV management by system operators in the future.[31]

Motivation

Germany remains the world leader in PV relative to total generation capacity (>20%) with approximately 7.2% of its energy needs met by PV in 2017.[32] Less than one quarter of its installed PV falls in the class of "residential" generation, though. During months like May and June, large percentages of the total system load is carried by wind and PV generation.

Function

Each PV system greater than 30kW in capacity is required to have a communication interface for DER curtailment signals. The specific communication technology is specified by grid operators and is typically radio ripple control. Smaller generators have the option to accept a permanent power limit of 70% of their system rating, but most opt to add the curtailment signal receiver. In response to a federal funding program for PV storage systems, many new PV systems (roughly 50%) are being deployed with energy storage to maximize self-consumption and obey feed-in power limitations. In order to qualify for the funding, PV systems must automatically limit exports to less than 50% of their nominal power rating.

Protocol

Versacom is the protocol used to communicate commands to inverters. It allows for addressing of groups of PV systems (grouped by distribution network service provider territory). Typically, curtailment is limited to discrete levels of 0%, 30%, 60% or 100% of the plant rating.

Network

There are two long-wave radio stations located in Germany that are able to transmit the digitally coded signals upon request. These were already in place for demand response purposes.

Management System

Responsible TSO or DSO send authorization to the long-wave station (operated by Europäische Funk-Rundsteuerung, or EFR) to have the code transmitted to the PV systems in their territory.

Interconnection Agreement

Participation in the ripple control program is required without compensation in the Renewable Energy Law, which governs the feed-in tariff.

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[31] AMI could allow for PV response feedback and more advanced inverter functionality in addition to other, non-PV related benefits.

[32] Recent Facts about Photovoltaics in Germany, Fraunhofer ISE, https://www.ise.fraunhofer.de/en/publications/studies/recent-facts-about-pv-in-germany.html, July 20, 2018.

Horizon Power

Summary

Horizon Power operates 38 isolated microgrids spread throughout regional Western Australia. Horizon Power has implemented PV management on a few of its isolated networks. The utility is experimenting with both direct communication and utilizing third-party aggregators.

Motivation

Customers have a significant interest in renewable generation and some isolated networks now have PV penetrations of up to 20% of installed generating capacity (any type). Horizon Power is witnessing dramatic effects from passing clouds where renewable energy penetration is high and the limited geographic footprint of the microgrid reduces spatial smoothing of PV. Without management of PV, some of Horizon Power's microgrids are unable to accommodate any additional solar generation, even with blanket feed-in restrictions in place.

Function

Horizon Power performs feed-in management with active power commands to inverters, instructing them to ramp down (or ramp back up) their power output. Additionally, a solar smoothing function is required for new systems once the so called 'unmanaged hosting capacity' for the microgrid is reached. This combines energy storage with PV to ensure that ramp rate limits are not exceeded.

Protocol

For purposes of PV feed-in management, Horizon Power uses the SunSpec protocol for all points between the SCADA system and inverter. As it looks to implement a DERMS package, it is mandating use of IEEE 2030.5 between the utility and prospective third-party aggregators.

Network

Communications travel from the programmable logic controller (PLC) over a corporate communications network to the town, then over a 100% private (Telstra) 3G cellular network to Cybertech modems at individual houses, and finally from the modem to the inverter. While this could be scaled, special attention would need to be given to data transfer costs.

Management System

Starting in 2014-15, Horizon Power began using a PLC at the control center to generate and send curtailment commands to the PV inverters. In Horizon Power's Carnarvon DER Trials they are using aggregator Reposit Power's platform to dispatch local PV and battery into a virtual power plant. The utility is looking to enable management by a DERMS and is currently running a tender process (requesting bids) for a DERMS package that will control DER directly as well as integrate with third party vendors.

Interconnection Agreement

Commercial-sized systems (> 50 kW) must be able to receive and act upon signals to ramp up or down by the utility, and all PV is required to perform solar smoothing with a battery once the "unmanaged hosting capacity" is met for its feeder. Small-scale PV feed-in management is being explored primarily in trials such Carnarvon.

Key Takeaway

Horizon Power has taken an aggressive stance on mandating open standards, first with their use of SunSpec Modbus and more recently IEEE 2030.5.

Energy Queensland (Lockhart River)

Summary

Energy Queensland is working with the Lockhart River community to demonstrate how high levels of solar generation may be adopted into isolated power systems.[33] Four large rooftop PV systems are managed during periods of high generation and light load to maintain stability on the standalone microgrid. The capability is successfully demonstrated, though a high degree of customization leads to significant implementation costs.

Motivation

Customer appetite for photovoltaic generation is growing, and limits for uncontrolled solar PV generation are being reached in many remote communities. Energy Queensland's isolated networks (such as the Lockhart River community) are predominantly supplied by centralized diesel generation and cannot rely on interconnected systems for support. Active management of solar PV generation serves the function of preventing generation from exceeding community loads (reverse power), and preventing damage to diesel generation assets due to extensive operation at low loads. The utility is interested in renewable generation—both decentralized and centralized—to displace diesel generation and reduce the costs of electricity supply in remote communities. In addition, monitoring solar PV generation enables effective spinning reserve management.[34]

Functionality

Dynamic monitoring and control is performed through a custom controller added at each of the 30-70 kW PV sites. The controllers gather information on solar PV generation and can curtail power from the plant upon command.

Protocol

Energy Queensland used Modbus RTU communications between the central diesel power station and the local controllers at each of the PV sites. These local controllers interface to multiple inverters at each premises over Ethernet via SunSpec Modbus communications.

Network

Due to the unreliability of the local cellular telecommunications network, a custom point to multi-point communications system was installed. An ultra-high frequency (UHF) radio links the central generation station and the four, managed PV sites. Cellular communication is used for

[33] Solutions tested in the Lockhart River community have not been tested in more urban environments and may not be directly transferrable to that use case.

[34] Effective spinning reserve for Energy Queensland requires sufficient but not excessive online diesel generation to be maintained to make up for rapid variation of solar PV generation in small communities due to cloud movement.

data collection and performance monitoring. Energy Queensland's longer term strategy is to leverage cellular communications and/or customer internet connections for smaller PV systems to reduce the customer costs.[35]

Management System

A programmable logic controller (PLC) at the central diesel power station continuously monitors the station power output, inventories diesel generating sets that are online, interfaces with the main station controller, calculates the maximum allowable output of solar PV generation, and provides a control signal to controllers at PV sites. The PLC dynamically gathers information from the PV sites on their total contribution to meeting community load and provides a spinning reserve offset to the main station controller accordingly.

Interconnection Agreement

Once unmanaged hosting capacity is taken up for a given isolated network, the next customer must agree for their installation to be monitored and curtailed on occasion. The long-term final details of any contractual agreement are being developed with the current expectation to set hosting capacities such that less than 10% of annual yield of solar PV installations is required to be curtailed.

Key Takeaway

Energy Queensland has witnessed first-hand how the lack of a common management platforms and communication interfaces has required an intense effort on the part of the utility.

Autonomous Volt-VAR and Volt-Watt Functions

New PV smart inverters in compliance with AZ/NZS 4777 or IEEE 1547-2018 (USA), among others, are now required to be capable of assisting in voltage regulation via autonomous functions, including:

- **Volt-VAR** – absorbs or injects reactive power in proportion to the voltage at the inverter terminals.
- **Volt-Watt** –reduces PV output in proportion to high voltage at the inverter terminals.

Advantages:

- Inverter response is dynamic and customized to current feeder conditions.
- Autonomous settings do not require external commands to provide a benefit, though communication may add to their effectiveness.

Disadvantages:

- Curtailment in response to voltage does not guarantee that system-wide generation-load balance is not exceeded. Supervisory control may still be necessary.
- Average inverter response is unlikely to be equitable among different inverters due mostly to inverter placement on feeder.
- Operates independently from other utility-controlled devices, necessitating careful setting selection in high-penetration areas to avoid potential conflict.

[35] For large systems, dedicated communications will be used to manage the network risks and prevent communication issues from significantly impacting yield of the solar PV installations.

Arizona Public Service

Summary

APS's Solar Partner Program (SPP) investigated the effects and potential benefits of advanced or "smart" inverters on the electric distribution system. The pilot project answered questions surrounding inverter settings, PV performance, hosting capacity, substation deferral, and distribution operations.

Motivation

The six research feeders included in SPP have some of the greatest penetrations of residential solar PV on any feeder in APS's service territory, an area of the United States that has some of the highest solar resource in the United States. The research feeders routinely experience reverse power flow (from distribution back to transmission) and residential PV installations continue to increase. While this does not yet have negative system-wide effects, local effects such as voltage rise are already being seen and expected to worsen with additional PV installations.

Function

PV inverters were equipped to perform active power limiting and reactive power functions such as Volt-VAR.

Protocol

Inverters that communicated over cellular used a form of Modbus between the operations center and the modem. Those that communicated over AMI used DNP3 between the radio network nodes and the operations center. Both used Modbus between the communication device (modem/AMI radio) and inverter.

Network

Inverters on the six research feeders communicated over a private (Verizon) cellular network while most other inverters that were part of SPP communicated over a proprietary AMI radio network.

Management System

Commands could be entered into basic human machine interface (HMI) that would replicate signals to a set of associated inverters. The system also acted as the contact point for inverters to communicate back to the control center.

Interconnection Agreement

Customers volunteered to be part of SPP and agreed to let APS own and install a PV system on their roof. In exchange for participation, the customer would receive a $30 bill credit each month for the duration of the 20-year roof lease.

Key Takeaway

APS's Solar Partner Program represents the largest rollout of utility-owned residential PV inverters by number (approx. 1600 residential customers). It thus provided increased understanding of smart inverter capabilities when under utility control.

Case Study Summary

A tabular summary of the case studies included may be found in Table 5.

Table 5
Summary of case study attributes, circumstances, and technological component subsystems.

Entity	Deployment Type	Drivers	End Use Technology	Comm. Network	Protocol	Management System	Interconnection Agreement
Hawaiian Electric	System-wide for all new customer-owned PV	High PV penetrations on isolated grids, trouble balancing generation & load	Disconnect switch in dedicated production meter	Private cellular	Proprietary AMI	AMI vendor's software portal	Export allowed except during grid emergencies (uncompensated during this time)
Japan	Multiple pilot projects	Aggressive renewable energy targets, favorable 2012 PV feed-in tariff, localized power surpluses & voltage violations	Various (custom for each inverter)	Internet (both public and private)	OpenADR	OpenADR server	Uncompensated curtailment during grid emergencies
Germany	System-wide for all new customer-owned PV	World's highest percentage of PV generation capacity	Radio receiver	Long-wave radio (one-way comm.)	Versacom	TSO/DSO sends authorization to long-wave radio station	Participation in radio ripple control program or production limit of 70% nameplate
Horizon Power	Multiple pilot projects	Witnessing dramatic effects from passing clouds, PV capacity limit reached in some areas	Cybertech modem at individual homes	Corporate comm. network to town, private cellular to modem at PV	SunSpec Modbus (IEEE 2030.5 between utility and aggregators)	Automated programmable logic controller (PLC) at control center	Perform solar smoothing with battery once "unmanaged hosting capacity is met", receive ramp-up/down signals (if > 50kW)

Entity	Deployment Type	Drivers	End Use Technology	Comm. Network	Protocol	Management System	Interconnection Agreement
Energy Queensland	Small demonstration project (four PV systems)	Small, isolated microgrids with PV capacity in excess of minimum load	Custom controller at four rooftop PV installations	Point-to-point ultra-high frequency radio, cellular for performance monitoring	Proprietary, low-complexity	Automated PLC at diesel power station	Unmanaged up to hosting capacity, mandatory agreement to management on occasion after limit is reached
Arizona Public Service	Large-scale pilot project (1600 inverters)	Routine reverse power flow (back to transmission) on research feeders, anticipated region-wide increases in installed PV capacity	Cellular modem at inverter	Private cellular OR AMI radio network	Modbus over cellular, DNP3 over AMI	Manual entry into HMI	Voluntary participation, $30 USD per month bill credit for duration of 20-year roof lease

Multiple other case studies were considered for inclusion in this summary, but only those that most closely aligned with Australia's challenge of managing small-scale PV were ultimately included. For example, deployments in Spain demonstrate management of distribution-connected PV systems over 5 MW in size,[36] but do not actively manage PV generation at the residential scale. Similarly, California has the most distributed PV of any US state at over 5,000 MW_{AC} (2016) with PV occupying 9% of single-family structure rooftops,[37] and yet it currently does not actively manage these systems. Additional examples of residential PV feed-in management may be expected as residential PV, and PV penetrations more broadly, continue to increase worldwide.

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[36] http://www.ree.es/sites/default/files/downloadable/folletocecre_v6_ingles_0.pdf

[37] https://www.nrel.gov/docs/fy17osti/68425.pdf

4
CONCLUSIONS

Feed-in management is far from a mature topic; however, it is receiving increasing interest globally. Australia is among the leaders in terms of overall energy production from solar and the amount of energy generated from residential PV systems. As a result, they are seeing a need to investigate PV feed-in management sooner than in other electric systems. While other areas have investigated this concept, previous solutions have often been experimental, small-scale, or reliant upon control of a smaller number of utility-scale systems. Very few places are experiencing the exact same issues as Australia or with the same urgency.

PV feed-in management capability has been demonstrated at scale, but there is no single, agreed-upon solution to do so, and preferred solutions in each instance are changing with changing needs and technologies. Regardless of the chosen solution, certain key elements are necessary to implement feed-in management:

- Device functionality
- A communication protocol
- A network architecture
- A management system
- An interconnection agreement

Throughout the process of preparing this report, several observations were made, including:

- Use of open standards may be necessary to avoid vendor lock-in and repeated costs for customization of communication networks and management systems.
- Needs for both device functionality and communication network performance may change as the number of PV interconnections continues to rise and different functionality or requirements are expected.
- Considering the full range of DER capabilities that may be desired over the next several years (beyond just real power feed-in management) may help avoid equipment and network upgrade/replacement costs, should additional functionality be desired before device end-of-life.
- Current interconnection agreements that allow feed-in management typically do so without compensation. However, periods of reduction are often limited in some way, either to a certain number of occurrences, a limited cumulative duration, or under specific grid conditions.

5
GLOSSARY

aggregator. A company (separate from the customer and the utility) that provides services to a utility by managing a group of customer resources.

AS/NZS 4755. Australian/New Zealand Standard - Demand Response Capabilities and Supporting Technologies for Electrical Products.

AS/NZS 4777. Australian/New Zealand Standard - Grid Connection of Energy Systems via Inverters.

backhaul (communications). A communication pathway between a centralized office or system and a remote point that partially aggregates local data before sending.

communication protocol. A set of communication functions that define syntactic interoperability between devices. i.e. the rules and structure that allow two or more entities to exchange information.[38]

DNP3 (Distributed Network Protocol). A set of communication protocols designed for communication between data acquisition units and control equipment.

feed-in. Energy flowing from distributed generation back onto the electric grid.

field area mesh network. A network consisting of various end devices (e.g. customer meters, voltage-regulating device radios, etc.) all connect to one another directly, dynamically, and without a set communication hierarchy.

hosting capacity. The amount of DER that can be accommodated anywhere without adversely impacting power quality or reliability under current configurations and without requiring infrastructure upgrades.[39]

IEC 61850. International Electrotechnical Commission standard on communication networks and systems in substations.

IEEE 1547. Institute of Electrical and Electronics Engineers Standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces.

IEEE 2030.5. Institute of Electrical and Electronics Engineers approved draft standard for smart energy profile application protocol.

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[38] Semantic interoperability may also be covered in protocols but is not always *required* as part of the protocol. For example, the DNP3 protocol can be used with custom points where the semantics of each input or output are defined outside of the protocol. Alternatively, there are application notes from the DNP3 Users Group where the semantics of specific points is standardized to help facilitate interoperability.

[39] https://static1.squarespace.com/static/598e0823e3df282e209b27b0/t/59f8bf5371c10ba76cf2a68a/1509474133047/Rylander_POG_Oahu.pdf

information model. A set of information (data models) and their organizational structure that defines semantic-level interoperability among devices and systems (at a lower level of detail than a communication standard). By definition, this type of standard facilitates interoperability, does not necessarily enable it.

OpenADR (Open Automated Demand Response). An open standard for electricity providers and system operators to communicate demand response signals with each other and with their customers using a common language over any existing IP-based communications network such as the Internet.[40]

PV. Photovoltaic; used in this report to broadly mean photovoltaic solar panels and the associated hardware that connects them to the grid.

ripple control. A communication method delivered via power lines (and typically used for load management) in which a high frequency signal is superimposed on the base 50 or 60 Hz power supply frequency.

RPA (reference point of applicability). An electrical point defined by IEEE 1547-2018 as "the location where the interconnection and interoperability performance requirements specified in this standard shall be met."

SCADA (Supervisory control and data acquisition). A control system frequently used for monitoring and control of utility devices.

small-scale/residential PV. Categorization used to describe PV systems, most often less than 10 kW, typically installed on residential rooftops.

SunSpec Modbus. A set of common register locations and interpretation (or mapping) for devices such as three-phase inverters or related measurement devices using the Modbus protocol.

Volt-VAR or **Volt-Watt**. Grid support functions available on many smart inverters that allows the inverter to vary its output of real (Watt) or reactive (var) power in response to local voltage conditions, usually at the inverter terminals.

[40] https://www.openadr.org/about-us

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