UTILITY-SCALE GRID ENERGY STORAGE

PURCHASE AND INSTALLATION GUIDELINE

SEIAPI Sustainable Energy

SIDSDOCK SMALL ISLAND DEVELOPING STATES ISLAND ENERGY FOR ISLAND LIFE

WORLD BANK GROUP

PPA PACIFIC POWER ASSOCIATION

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These guidelines have been developed for The Pacific Power Association (PPA) and the Sustainable Energy Industry Association of the Pacific Islands (SEIAPI).
They represent latest current industry knowledge on Utility Scale Grid Energy Storage

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List of Abbreviations

A summary of the main acronyms and terms used in this document is listed below:

AC	Alternating Current
AS	Australian Standards
AS/NZS	Australian and New Zealand Standards
BMS	Battery Management System
BOS	Balance of System
CAES	Compressed Air Energy Storage
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DC	Direct Current
ESS	Energy Storage System
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization

Abbreviations

LCOE	Levelised Cost of Energy
LFR	Lithium-Iron-Phosphate
Li-ion	Lithium ion Battery
LMO	Lithium-Manganese-Oxide
LTO	Lithium-Titanate-Oxide
MPPT	Maximum Power Point Tracker
MV	Medium Voltage
NaS	Sodium Sulphur
NCA	Lithium-Nickel-Cobalt-Aluminium
NEC	National Electricity Code
NMC	Lithium-Nickel-Manganese-Cobalt-Oxide
Ni-Cd	Nickel Cadmium
NiMH	Nickel Metal Hydride
NRECA	National Rural Electric Cooperative Association (US)
PLC	Programmable Logic Controller
PSoC	Partial State of Charge
PV	Photovoltaic
RE	Renewable Energy
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SIB	Sodium-ion Batteries
STC	Standard Test Conditions
VA	Volt-Ampere
VAR	Volt Amperes Reactive
VRLA	Valve Regulated Lead Acid
Wh	Watt-hour
W_p	Watt peak (also known as peak-Watt)

1. Introduction

With the increase in preference for renewable energy over conventional fossil fuels for power generation, the additional complexities of generation fluctuations that may be due to the intermittent nature of some renewable sources is a matter that requires careful consideration and planning. The electric power grid's reliability and resilience can be disturbed with variable renewable energy sources replacing conventional fossil fuel generation. One means of enhancing the grid reliability is through utility-scale grid energy storage. This is a method of storing energy at utility-scale within an electrical power grid. The stored energy can be sourced from the existing fossil fuel generation (by charging energy storage systems) or from excess renewable energy production from sources such as solar or wind power that can sometimes generate more energy than needed during periods of low energy demand. The renewable generated energy could also be curtailed by the grid operator due to issues like grid congestion, lack of adequate transmission infrastructure etc. This excess generated renewable energy can be captured and stored in utility-scale storage systems such as batteries, capacitors, flywheels, pumped hydro or compressed air energy systems. These systems can provide short-term or long-term storage depending on the scale and technology implemented which could provide for peak-shaving, voltage and frequency regulation, power quality enhancement, load-levelling/balancing and load shifting applications.

Energy storage technology can be chosen based on different requirements including frequency response, peak load shifting, storing excess renewable energy capacity, renewable energy penetration levels, spinning reserve requirements, peak/off-peak loading, capital cost, efficiency, market trend, environment suitability etc.

This guideline discusses different grid energy storage options; their advantages and disadvantages for grid storage and the other key system component - inverters and how energy storage is being applied to allow higher penetration of renewable energy onto the grid and in particular focusing on the issues faced by the Pacific Island Utilities.

Note: Though renewables could include wind as well as solar, it is appreciated that in many of the Pacific Island countries the only renewable resource being connected to the grid at a large scale is solar power. In this guideline when describing system operation, in particular the relationship between the existing fuel generation and the renewable generation, the descriptions focuses on solar power being the renewable generation. Some key differences when applying the logic to wind generation is that it is potentially available in the night time while the solar generation is not and its availability is less predictable than solar.

2. Why Have Energy Storage?

The intermittent nature of renewables can affect the stability of the grid and possibly require the utility operator to maintain sufficient fossil fuel generator spinning reserve to reduce the economic advantage in using renewables. With storage, the levels of penetration of renewables, both in power and energy, can continue to increase. The ambitious targets of 100% renewable penetration will not be reached with solar or wind without energy storage.

2.1 Grid Stability – Frequency and Voltage Support

Particularly with diesel generation, rapid changes in the power demand can result in fluctuations in the operating frequency and voltage on the grid and therefore lead to grid instability that can affect the loads connected and may even cause outages if the fluctuations are greater than that allowed by the grid controls. If the fluctuation is caused by rapidly increasing loads, the result is that initially the generator may slow (hence reduce frequency) until the control system of the generator increases the speed and returns the frequency to the specified requirement, either 50Hz or 60Hz depending on where the system is located in the Pacific. If the sudden change is too great it can also lead to a rapid reduction in voltage and again the generator control system should allow the generator to provide the extra power and voltage needed to return to the specified level. The sudden loss of a large load can have the opposite effect: speeding up of the generator with associated higher frequency and increased voltage.

If the actual load becomes greater than the output of the operating power generation then the operator will compensate by increasing the available generation capacity. This is usually obtained by maintaining a specified spinning reserve. Likewise, if the actual load falls, generators may be shut down or transferred to spinning reserve.

Intermittent renewables can have the same effect on the grid as variations in loads. That is if a large solar power plant is located in one spot and cloud covers the solar array, the loss of power from the solar array has the same effect as suddenly increasing the load on the main grid. Conversely, the passing of the cloud then causes a sudden increase in solar power that is seen by the grid as a sudden loss in load demand. Figure 1 shows how a large steam powered generator regulates in response to changes in frequency compared to the response of an energy storage system (Figure 2). The steam generator and energy storage system are both connected to the South Australian grid. The energy storage system is a Tesla 100MW/129MWh battery located in South Australia. Large fossil fuel generators used in the Pacific respond very similarly to steam powered generators. It can be seen how the battery system responds much faster than the rotating generating system.

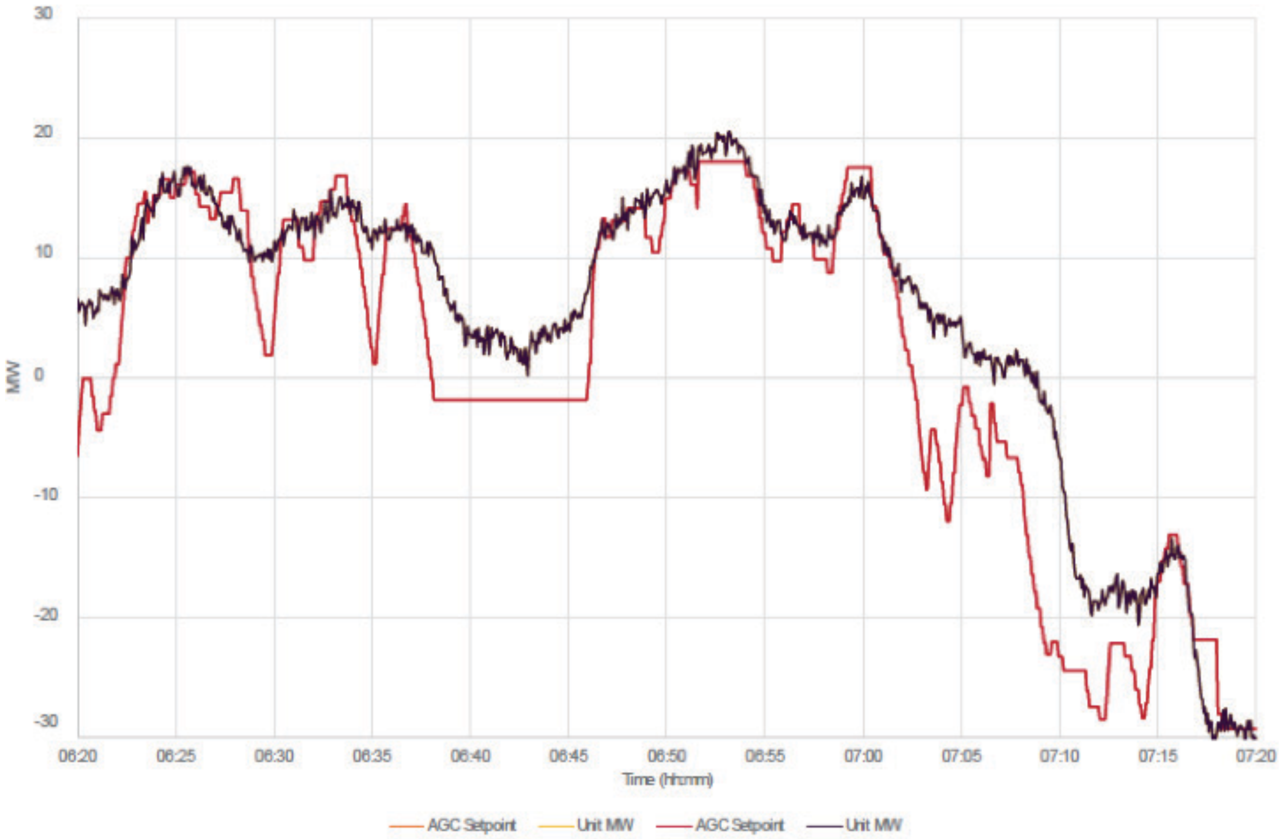

Figure 1: Accuracy and speed of regulation frequency control ancillary services- steam powered generation

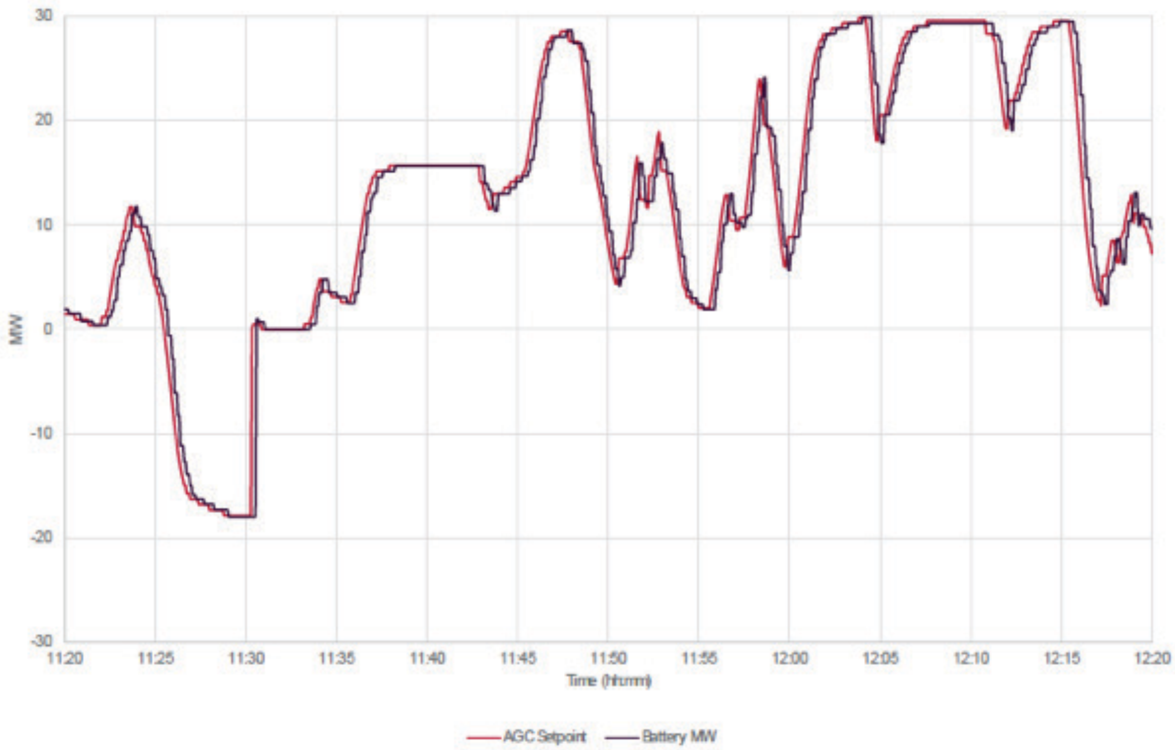

Figure 2: Hornsdale South Australia Power Reserve- Accuracy and speed of regulation

Both figure 1 and 2 sourced from:

Initial Operation of the Hornsdale Power Reserve Battery Energy Storage System-AEMO April 2018

Discharging of energy storage systems (acting as a generator) and charging (acting as a load) can also be used to maintain voltage stability. If the voltage is increasing due to an excess in generation then the battery can absorb this excess energy and reduce the voltage. If the voltage decreases (voltage droop) due to an increase in power demand, then the energy storage system can discharge into the grid acting as a generator. Note that to allow this to happen, the battery must, on average, be at a partial state of charge to allow it to either absorb excess power or deliver added power to the grid. Thus to function well, there must be a battery charge control system that continually adjusts the charge level of the battery system either by delivering excess charge to the grid or absorbing power from the grid to bring the charge up to the optimum value.

2.2 Spinning Reserve, Smoothing and Capacity Firming

There should be a sufficient level of spinning reserve available within the power generation facility to manage a sudden increase in power demand. The size of this spinning reserve is dependent on historical power demand patterns and also what are the characteristics of the different generators that the particular power generation system has available. Generators available as spinning reserve can be known as dispatchable power generators that are brought on line as required.

Due to the high variability of solar and wind generation, utility operators may need to maintain a high spinning reserve capacity to ensure that the grid frequency and voltage remain stable. Energy storage could be supplied with the renewable energy system so that the energy storage provides the spinning reserve. This then has the outcome of “smoothing” the renewable energy generated power as seen by the utility operator.

Using energy storage in place of spinning reserve reduces the need for using fuel generators as spinning reserve. Spinning reserve is burning fuel constantly even though not contributing to generation. Also the generators on spinning reserve are generally operating at a low load and often will be incurring higher maintenance costs. Therefore, instead of sizing the energy storage to provide for continuous generation, the energy storage can be sized just to allow sufficient time for the utility operator to start another fossil fuel generator to meet the extra demand then when it is on line the storage can be recharged.
This avoids the high fuel and maintenance cost of operating spinning reserves.
In this configuration it can be designed so that the renewable energy generator combined with the energy storage can provide a specified level of power generation continuously (sometime called capacity firming) over a certain period of the day. In this scenario monitoring will be required so that if there is a major change in the availability of the renewable energy resource, e.g. cloud cover that will last a few hours, the energy storage provides generation for sufficient time to allow the operator to bring more generation online, typically one hour or less.
This scenario where the renewable energy generator is combined with the energy storage for capacity firming also means that combined, they can now become a dispatchable generator within the grid. However, this should not be at the expense of losing the economic advantage of the solar providing power into the grid and reducing the use (and hence expense) of diesel.

2.3 Power Rate Limit (Power Ramping)

Fuel generators providing power into a grid typically have excess generation capability (their spinning reserve) so excess generation capacity is available so any expected excess loads can be supplied effectively. Similarly, when loads decrease, the power coming from the fuel generator ramps down accordingly and increases its spinning reserve.

However, when the output from a solar power system is affected by clouds, the loss of solar power is very rapid. That is, there is insufficient time for the ramping up or down of the available diesel generation. This sudden change often causes fluctuations in voltage and frequency within the grid.

Recent inverter standards have specified the power rate limits for new inverters that include this facility. The power rate limit is the ramp rate of real power output in response to changes in power. It is specified as a percentage of rated power per minute. The nominal ramp time is the number of minutes it takes for a 100% change in rated power for the system. For example: The Australian and New Zealand standard: AS/NZS4777.2, Grid connection of Inverter Systems – Part 2 Inverter Requirements specify a default rate of 16.67% which would be 6 minutes to change from no power to full power.

If the inverter has this function, when the solar power is suddenly available after a cloud cover passes then the available power from the solar array will immediately rise up from the power available while the array was being shaded to the power available after the solar array is free of cloud shading. In real time this will take seconds only, but the exact length of time seen by the grid will be dependent on the ramp rate set, the actual solar power available while shaded and what would be delivered not shaded. Basically, the inverter is acting as a gate to allow the power to enter the grid and the gate is opening slowly enough to allow the fuel generators to follow the changing conditions.

Worked Example 1

The solar array system has a rated output of $500kW_p$ connected to an inverter rated at 450kW.

The up ramp rate on the inverter has been set at 16.67% therefore the inverter would ramp up be:
16.67% x 450kW per minute = 75kW per minute.

Assuming the system is covered by cloud and produces 25kW. When the cloud moves away and the array is unshaded it produces 350kW. The time taken for the inverter to ramp from the 25kW to 350kW = (350kW-25kW) / 75kW per minute = 4.3 minutes.

However, when the solar array loses power due to a cloud suddenly shading the solar, then the inverter is unable to apply the proper ramp rate unless energy storage is available to deliver the power to fill in the power reduction by the solar enough to slow the decrease in solar input seen by the grid to the acceptable ramp rate. When storage is available, the ramp rate can even be set at a lower rate so that it would take longer for the combined solar and energy storage power to ramp down in order to provide the grid operator time to turn on or ramp up other sources of generation to fill in for the lost solar power generation.

As an example, Horizon Power in West Australia requires a ramp down time (if storage is available) of 12 minutes, that is a ramp rate of 8.3%.

Worked Example 2

The solar array system has a rated output of 500kW$_p$ connected to an inverter rated at 450kW.

The down ramp rate on the inverter has been set at 8.3% therefore the inverter would ramp down: 8.3% x 450kW per minute = 37.5kW per minute.

So no matter what the solar array is producing if it suddenly loses power due to cloud cover its output must ramp down at 37.5kW per minute.

Using the data from example 1, assume the array is producing 350kW and when shaded it will produce 25kW. The time taken for the system to properly ramp down from the 350kW to 25 kW = 350kW-25kW / 37.5 kW per minute = 6.67 minutes.

2.4 Storage of Excess Solar Energy

During the day the loads on the grid will be supplied by the power being generated by the existing fossil fuel generators plus the power that is available from the solar array. The dynamics of the system are that the loads will be varying, while the available solar power will also vary based on the available solar power (irradiance) and the fuel generator power output will also have to vary to ensure that the loads are supplied quality power.

Depending on the system configuration it is not uncommon for some utility operators to control the system to ensure that the fuel generators have a minimum power loading in order to achieve optimal fuel efficiency. This may result in having to reduce the available solar power generation to a specified amount that is less than its actual capacity. Modern inverters typically used in utility operations can do this by the inverter ramping down its input by moving its input voltage down the current-voltage characteristic (IV curve) of the array from the maximum power point to the voltage that provides the specified maximum PV generation.

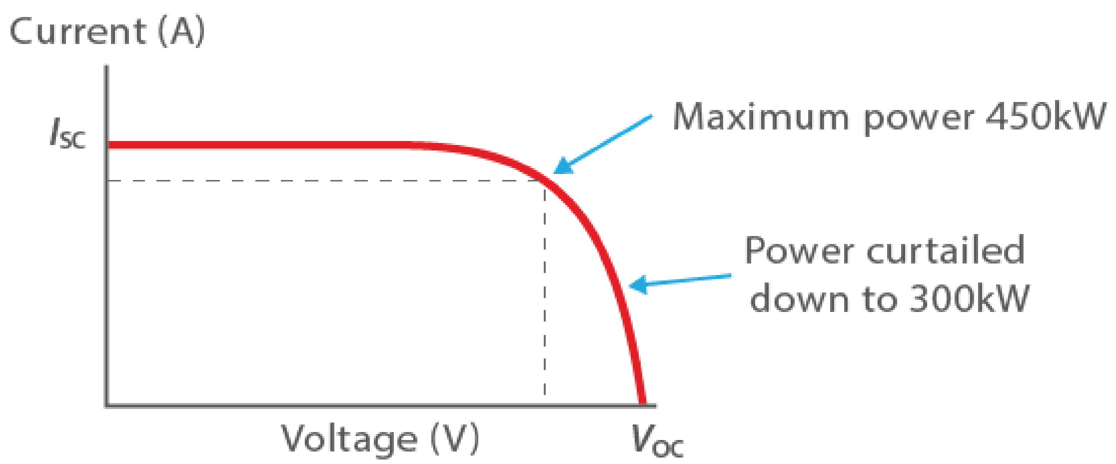

Figure 3: Curtailing of solar power by ramping down IV curve

If energy storage is available, then the excess solar power does not need to be curtailed it can be stored. This will allow the otherwise lost energy to be made available to meet other requirements such as ramp down, peak demand, etc.

2.5 Peak Demand Lopping or Peak Shaving

During the 24-hour day there are usually one or more periods where the demand is higher than the average and often only for relatively short periods of time. Most Pacific utilities see a daytime peak based on government and commercial use and an evening peak based on residential use. This situation often requires additional generation capacity to come online to meet these short-term higher demands.

Depending on the size of the extra demand the required additional generation could be provided by energy storage as shown in Figure 4.

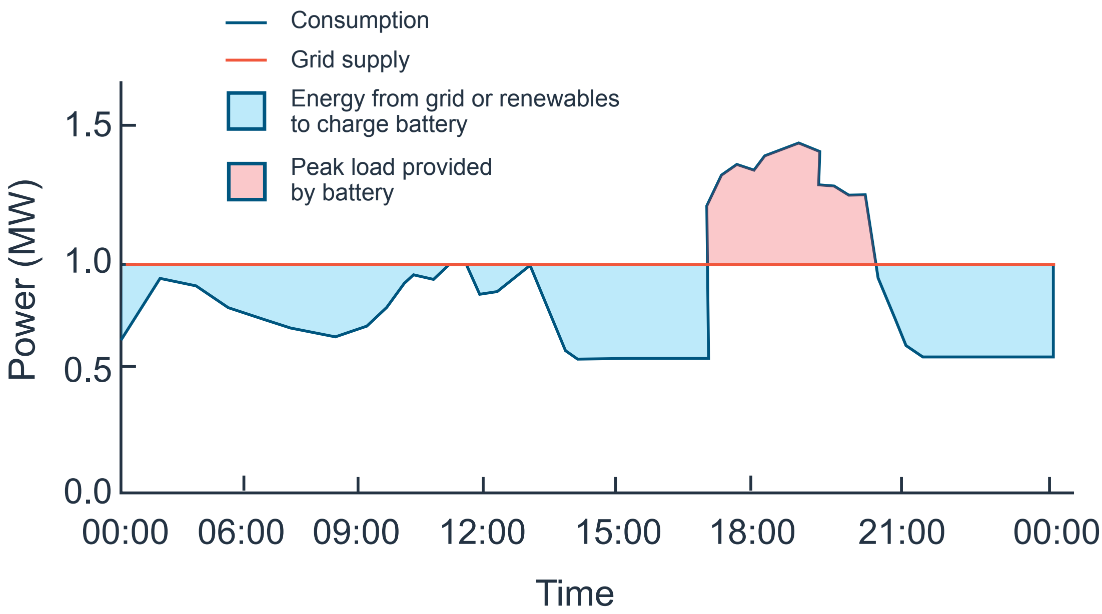

Figure 4: Peak Demand Lopping

The charging of the energy storage charging could either come from the grid, thereby providing the fuel generation with a more constant load and better fuel efficiency or from excess renewable energy generation depending on the actual configuration of the system.

2.6 Operation with no Fuel Generators Generating in Daytime

A number of Pacific Island countries and territories have targets to have 100% renewable energy generation. This will not occur if solar or wind is the generation source without substantial energy storage. To meet 100% energy demand with renewables that include solar or wind will require energy storage systems that will deliver the needed energy when the renewables are not generating sufficient power to meet prevailing demand, e.g. for solar that includes early in the morning, late in the afternoon and when there are extensive clouds.

One step in this objective for 100% renewable energy generation would be to have the renewables and energy storage meeting the daytime requirements. This is the objective of the current project planned for Tuvalu. In this situation the renewable generators, in these cases solar systems, will need to be sized to provide all the energy required during the day. The solar energy storage system would then provide the capacity firming for the system but more importantly provide added power when the available solar power is less than the power demand of the load. In this situation, the main energy storage inverter will be the grid forming inverter when there is no fuel generator operating and all other inverters will synchronize with it.

2.7 End of Grid Support

At the end of distribution lines, low voltage can sometimes be a problem for the grid operator. This problem has sometimes resulted from an increase in power demand and can be overcome by upgrading the distribution network. However, particularly with underground cables, this could be expensive and hence why energy storage (and possibly solar power) could be considered. Locating energy storage systems at the transformer or in a suitable location on the distribution allows the energy storage system to supply power to the distant parts of the grid and keep the voltage in an acceptable voltage range.

2.8 Reactive Power Support

Capacitors are the typical device used by grid operators to provide power factor correction throughout the grid. Small solar power systems typically only inject real power into the grid and thereby contribute to a lower power factor on the grid.

A low power factor affects the stability of the grid and it can cause heating and overload hazards for transformers and transmission equipment. The highly distorted current waveforms drawn from the grid can lead to higher order harmonics being fed back on the grid.

Some grid connected inverters are able to provide reactive power onto the grid and thereby help to maintain a higher power factor delivered from the site where the solar power system is located. This tends to be only included on larger solar systems. When there are many smaller, distributed systems these probably will still operate at unity power factor.

The overall issue can be overcome by using standard power factor correction capacitors however the energy storage systems and their associated inverter could also be used to inject reactive power onto the grid.

3. Inverters

A grid-connected Inverter or Power Conditioning Equipment (PCE) converts dc electricity into ac electricity with voltage and frequency suitable for injection into the utility grid. For a grid with a battery energy storage system, a bi-directional grid-connect inverter or power conditioning unit with a control system specific for the battery technology is generally used. However, in some of the smaller systems in the Pacific islands, the battery inverter might be the same as those used in off-grid power systems and it is the grid-connected inverter that interconnects the solar array and s energy storage systems to the grid. A grid-connect battery inverter, apart from converting dc to ac electricity at required voltage and frequency for connection with the grid, will usually also convert ac to dc electricity for charging the batteries. These battery inverters play a crucial role in the integration of energy storage systems with the renewable energy power source, diesel power plant (if any) and the electric power grid. Apart from converting dc to ac and maintaining charge/discharge cycles of batteries, battery inverters along with grid connect PV inverters are required to perform various other functions for smooth grid operation like power factor and reactive power (kVAR) support, ramp rate provision during transitions, and offer configurable voltage and frequency trip points to meet the network regulatory requirements.

When selecting an inverter to be used in a grid connected PV system, they shall meet either:

- IEC62109 Safety of power converters for use in photovoltaic power systems
    - IEC62109-1 Part 1: General requirements
    - IEC62109-2 Part 2: Particular requirements for inverters

or

- UL Standard 1741 Standard for Inverter, converters, Controllers and Interconnection System Equipment for use with Distributed Energy Resources

Battery systems for utility scale grid storage are usually equipped with a Battery Management System (BMS) that is manufactured and designed specifically for the battery chemistry and operation in use. The BMS unit of the battery storage system monitors and controls the charge and discharge processes of the battery system such that the lifetime and safety of the battery are maintained. The Battery Management System (BMS) of batteries for utility-scale grid integration usually have a complex hierarchy of control architecture that includes master-slave control modules that co-ordinate amongst them the charging and discharging of each module. The grid-connect battery inverter is connected to the batteries and inverter communication with the BMS should be established to share the battery attributes and charge/discharge status. It is important to select a grid-connect battery inverter that is compatible and can inter-operate with the battery's BMS.

Utility-scale power systems employ either separate large central inverters or many smaller inverters. Central inverters usually are of the range 500 to 2500 kW whereas small inverters within the system can range from 10 to 250 kW. Depending on the system design, the inverters for energy storage can either be PV-battery-inverters or hybrid (multimode) inverters. Hybrid inverters are built to function as both a grid-connect PV inverter and as a battery inverter. They can interconnect the PV array and battery system to the grid while discharging the battery and also operate as a battery charger for charging the batteries by using energy from the grid.

The inverters can be of transformer or transformerless topologies and depending on the topology, the medium voltage (MV) transformer configuration connected to the inverter varies. A standard unipolar inverter may incorporate a LV transformer for the required ac voltage output and galvanic isolation between ac and dc side of the inverter is thereby provided. However, an additional, external transformer is required to step up the voltage to MV levels for transmission. A transformerless inverter does not have an inbuilt transformer and it directly couple's ac output of the inverter to the MV transformer. This type of inverter increases step-up efficiency as there is only a single external transformer, unlike the transformer inverter that requires an additional external transformer before integration into the grid. However, transformerless inverters require additional protection for galvanic isolation provision to prevent dc injection into the ac grid or ac injection into the dc side.

Inverters connected to the distribution grid are required to function at unity power factor and they must shut down when there is a grid disturbance to enable the anti-islanding safety feature as per UL 1741. But this cannot be the case for the utility-scale inverters as having the inverter shutting down to this response only exacerbates the existing grid instability. Hence it is important that the grid-connect battery inverter is chosen that can provide dynamic grid support that is compatible with the requirements set by the utility. Some inverters are designed to allow pre-configured dynamic grid control functions but at the utility-level integration, the battery inverters should be able to follow instructions from the Power Plant Controller or the SCADA as well.

3.1 Energy Storage Coupling Architectures

The integration of battery systems with PV power systems and the utility grid not only differs with different types of batteries but also with different system architectures. The battery can be coupled to the PV system on either the ac or dc bus resulting in two basic system architectures: ac coupled systems and dc coupled systems.

Efficiency of the system plays an important role in economics of the project. Both system architectures have their own set of advantages and disadvantages and they need to be chosen carefully depending on the utility requirements and limits, site conditions, grid service required based on the level of renewable integration, ease of installation, communication and interoperability features, scalability, and reliability. Specific grid applications will decide the design of the battery inverter's controller architecture for utility-scale storage integration. For example, an energy storage system required for a load levelling application will allow pre-set loading conditions of the transformer and transmission lines to which it is connected. But with renewable energy integration into the grid, these control architectures will also provide for dynamic grid support which cannot have pre-determined limits, such as the magnitude of active and reactive (P and Q) power, setup beforehand in the inverter. Hence the inverter should have to perform based on the dynamic inputs provided by the plant controller.

The inverters on the market should be analysed for the particular grid functions that they are designed for, compatibility with the energy storage system chosen for the application, their safety and performance attributes, the balance of system components incorporated with the inverter system, warranty duration, bankability of the inverter and the manufacturer. All these factors will decide the LCOE (Levelized Cost of Energy) of the entire system.

3.1.1 ac coupled systems

This is the most common method of incorporating an energy storage system to a utility scale PV system. In this method of integration, a separate PV inverter and a bi-directional battery inverter are required and the outputs of these inverters are paralleled at the ac bus of the system. This is the configuration usually used when a battery energy storage system (ESS) is required to be retrofitted to an existing PV system connected to the grid. There is no need of re-wiring the dc side of the PV inverter for storage integration. This system configuration has that advantage as much additional capacity as required can be added at any stage in the future.

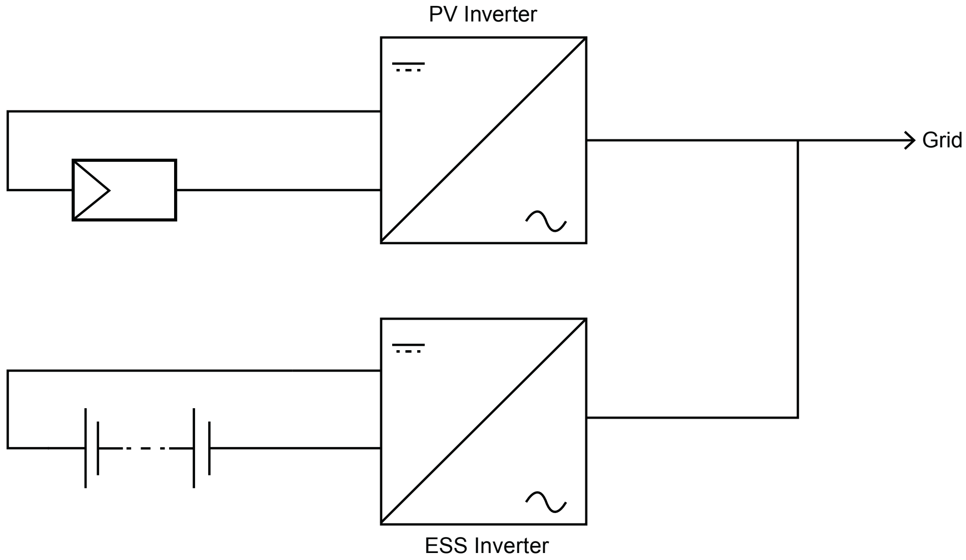

Figure 5: ac Coupled System Configuration

The overall system efficiency for this configuration can be lower compared to the dc coupled system, as there is additional power conversion required at the battery inverter stage. That is, losses associated with conversion of ac to dc to charge the batteries and conversion from dc to ac for grid supply results in comparatively lower system efficiency. This double conversion loss should be taken into account when sizing a battery storage system for retrofitting to the PV system which may result in a slightly larger battery size than required for a dc coupled system. Again, there are various factors including conversion efficiencies, distances between the major components and the sub-station for voltage drop considerations, capital and installation costs etc., that play a more major role in sizing the battery.

In this system configuration, the combined power input to the electric grid can be maximised delivering both all available power direct from the PV into the grid and simultaneously discharging the battery at maximum power. Grid service requirements like ramp rate control, load levelling, peak shifting and capacity firming will require an ac coupled energy storage system design. However, if the output of the PV system is curtailed due to grid restrictions (e.g. due to limitations on the local grid infrastructure) or an outage due to a fault or maintenance, this arrangement does not allow the excess solar power to be used for charging batteries unless there is some control mechanisms between the two inverters and secure isolation from the grid.

Operational experience for this type of system configurations at the utility-scale level is now abundant. The necessity for separate PV and battery inverters and separate MV transformer stations on the ac bus for integration with the grid increases the outlay for the system. Apart from these, the interoperability for this system configuration is more complicated than the dc-coupled system due to completely different systems for each energy source (PV and battery) requiring dedicated operation to achieve their integration into the utility grid. Continuous monitoring and control of both the systems is absolutely critical in this configuration in order to maintain grid integrity hence sophisticated monitoring and control or SCADA is required for smooth operation. If the inverters are mis-matched at the design or installation stage, it may hinder monitoring of individual systems resulting in inefficient grid operation or even grid failure.

3.1.2 dc coupled systems

In a dc-coupled system, the battery energy storage system is connected to the dc side of the PV inverter as shown in Figure 6. In a utility-scale energy storage system, dc coupling is relatively a new approach for retrofitting battery storage system to an existing PV system. The battery storage system is connected to the dc side of grid-connect PV inverter via a dedicated Battery dc-dc converter. Operation of this system is much simpler than an ac-coupled system given there is less equipment requiring dedicated monitoring solutions.

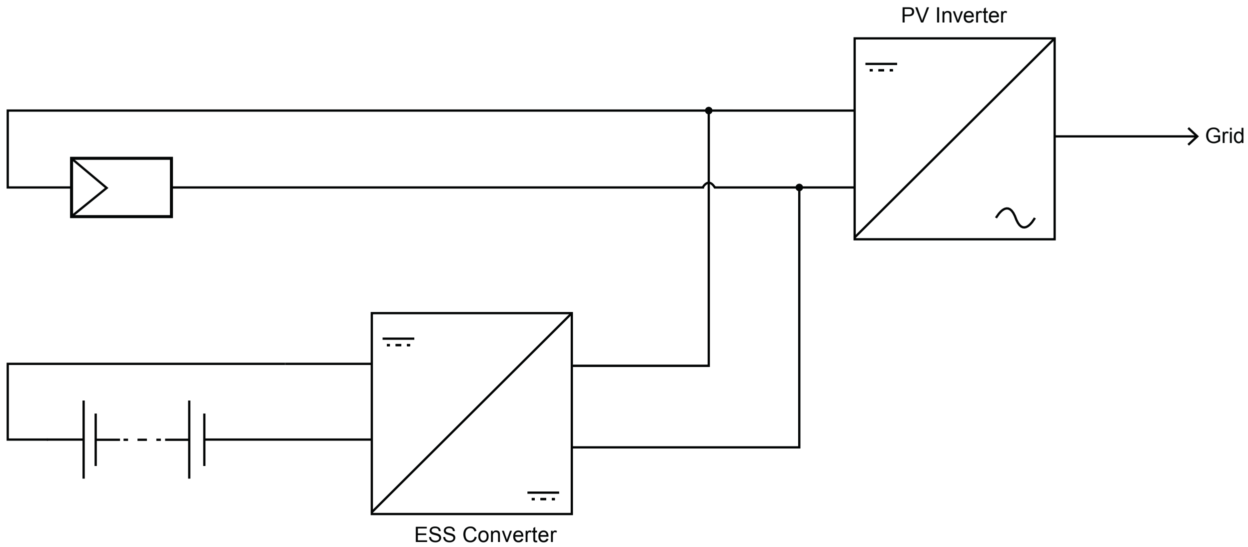

Figure 6: dc Coupled System Configuration

Energy Storage System integration with the PV system connected to the grid in this configuration has two major advantages compared to the ac coupled systems: lower capital installation cost and higher system efficiency. The lower cost is mainly due to the avoidance of the need for installation of an MV transformer station at the ac output of the Battery inverter as in an ac coupled configuration. But the use of dc-dc converters to step up the battery voltage to MV dc level as required by the inverter input is not yet a mature technology and this could possibly mean that the cost of this equipment could be significant for this type of system configuration.

This system configuration doesn't involve the double conversion efficiency factor at the battery storage system as in an ac coupled system. The energy curtailed, due to grid restrictions or an outage due to a fault or maintenance, can be recaptured by the battery for storage via the ESS dc-dc converter. The PV inverters require a minimum threshold voltage to wake up the inverter to start its operation. This wake up voltage is usually required in the early mornings or when there is cloud coverage on the PV modules resulting in rapid decrease in Maximum Power Point voltage. This wake up voltage required can be provided by the energy stored in the battery installed on the dc side of the inverter. In addition to this benefit for inverter start-up, this configuration allows for the marginal energy generated by the PV to be captured for energy storage. Besides these advantages over ac coupled system, the dc coupled system configuration provides ramp rate control, energy time shifting, capacity firming, clipped and curtailed energy recapture, and low voltage harvesting from the renewable energy source.

With increasing availability of PV/battery inverter systems and dc-dc converters for utility scale systems, the dc-coupled system configuration could soon be an economically feasible choice for solar-plus-storage utility scale projects. One main disadvantage of a dc coupled system over an ac coupled system is that the size of the battery storage system is restricted by the size of the PV inverter if the energy storage system is to be retrofitted to an existing PV system.

3.2 Separate Inverters and Hybrid Inverters

A grid-connected battery bi-directional inverter separate from the PV grid-connect inverter is often installed for grid storage applications. A utility scale grid connected PV inverter is required to provide grid functions such as: Active power reduction; Reactive power capability; grid voltage stabilization; dynamic grid support (Voltage Ride Through). In addition to the grid functions that the grid connect PV inverter provides, a grid connect battery inverter shall also perform functions such as load levelling, frequency regulation, ramp rate control, peak power shaving, and maintain and support grid stability and power quality.

Separate Battery Inverters can be used in both ac and dc coupled system architectures increasing design flexibility. In an ac coupled system, a separate PV inverter and a bi-directional battery inverter can be connected on the ac bus that is then connected to the sub-station. In a dc-coupled system, separate dc-dc converters for PV and Battery can be connected to a Hybrid Grid connect inverter on its dc side; or a battery dedicated dc-dc converter can be connected to a grid connect PV inverter in its dc side. The MV sub-station shall then be connected to the AC side of the grid connect Hybrid or PV inverter usually in a separate sub-station enclosure. A utility-scale Hybrid inverter like the utility-scale dc-dc converter is not a mature technology yet but it can support both solar generation and energy storage using a single inverter i.e. it can track the MPPT of the PV array as well as perform charging and discharging of batteries. The dc input voltage from PV and batteries should both be considered when designing and choosing a hybrid-inverter system.

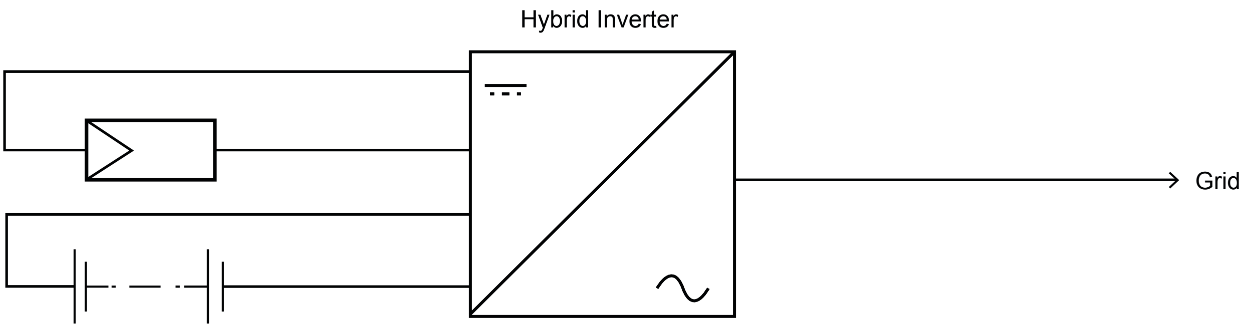

Figure 7: Hybrid Inverter System Configuration

Selecting inverters dedicated for battery storage on grid also requires designing and selecting an appropriate enclosure with required protection that is temperature and humidity controlled and has wiring, switchgear protection components on both the dc and ac sides of the inverter, MV switchgear and transformer. Some of the commercially available utility-scale bi-directional battery inverters are provided by ABB, SMA, Power Electronics, Sungrow, Leonics, etc.

3.2.1 Other system components

Apart from the inverter requirement for communication with the battery BMS to control charging/discharging regimes and integration to the grid, there are other Balance of System (BOS) components required for safe operation of the system. Some of these components required are battery input protection, Battery Inverter protection, dc busbar protection, battery inverter ac busbar protection, interconnection wiring, ac feeder protection, transformer protection, dc supervision and control monitors. Some inverters like the Dynapower CPS-500 inverter have integrated cooling, ac and dc switchgear and protection pre-wired and installed within the inverter enclosure. Additional protection equipment should then be installed for battery dc inputs and transformer ac inputs outside the inverter enclosure as not all products provide switchgear room within the inverter enclosure.

3.3 Integrated Battery and Inverter Systems

The utility scale inverters today mostly come as a packaged solution that allows a plug-and-play type installation in the field. It houses two or more inverters with a medium voltage (MV) transformer, ac and dc switching and protection devices, monitoring and control devices all within a climate-controlled enclosure which is usually a shipping container or a structure on a skid.

The availability of integrated solutions for utility scale integration of energy storage systems has increased now that major inverter market players like ABB, Power Electronics, SMA etc. provide turnkey solutions for battery integration into the utility grid. These integrated systems have dedicated battery racks for battery installations, that can be readily connected to battery inverters and establish communication with the battery specific BMS units, interconnecting equipment, switchgear and protection equipment. In some cases, a MV transformer is connected to the battery inverter and all these components are set up within a single enclosure that is usually a shipping container. These integrated systems reduce the number of additional BOS components required making installation of the system easier and faster. This again reduces the costs and complexities associated with installation and logistics since all the materials come from the same source and are assured to work together. Other advantages of such integrated battery inverter systems include ease of control and monitoring, enhanced operation and maintenance due to efficient inter-operability and, increased safety. Most of the integrated solutions available are modular systems allowing easy up-scaling by adding another energy storage system container. The containerised energy storage solutions are available ranging from 250kW and up. Similar sized energy storage container systems can be paralleled to increase the installation capacity as required. The components are all pre-integrated and pre-configured for direct installation in the site that it saves time, initial capital investment and additional labour costs.

For example, Redflow has a Large Scale Battery platform that is an integrated energy storage solution with Zinc Bromine flow batteries. It includes 45 Zinc Bromine flow batteries connected to six 12kW Victron battery inverters in a 20-foot shipping container that can provide 450kWh total capacity. This energy storage system in the container can be modified with more or less number of batteries or other compatible inverters that may vary based on the utility requirements and then shipped to the site of installation for easy and fast integration into the existing PV system or diesel power plant. The container itself is designed to control the temperature and humidity for optimal battery and inverter performance. The All-in-one solution enhances operation and maintenance efficiency as the communication interface is all pre-configured for inter-operability.

These plug-and-play solutions available in market now only enable ac coupled system implementation. With added benefits of reduced capital costs, labour costs, installation time, operation and maintenance complexities, the integrated energy storage system is fast becoming a dominant choice for utility electric power grid integration.

4. Where Should Energy Storage Systems Be Located?

Energy storage can be located at the power station, at the site of the renewable energy generator or sometimes where land is available that allows a proper grid connection for the size of the storage to be installed. The best location is primarily dependent on the purpose of the energy storage system. Another factor is the dispersion of the renewable energy generation. If all the highly variable renewable generation – generally from solar or wind systems, are all in one or two large farms then that can have a different effect on the grid compared to the effect of many relatively small sized solar or wind systems distributed throughout the grid.

4.1 Grid Stability – Frequency and Voltage Support

When the energy storage system is to provide frequency or voltage regulation at a power station then the most cost-effective location will be to have a suitably sized energy storage system located at that power station.

However, if the installation of the energy storage system has a number of objectives (e.g. ramp rate control, capacity firming) in addition to frequency and voltage regulation, these other objectives may be the dominant objectives. In that scenario the energy storage system would generally best be suited at the site of the renewable energy system.

Varying voltage levels is an issue on the distribution system as well as at the power station. So if the energy storage system is to provide voltage support due to the highly variable renewable energy supplied to the grid, then the energy storage system should be located at the site of the renewable energy system.

4.2 Spinning Reserve, Smoothing and Capacity Firming

When the energy storage system is only to provide “spinning” reserve so that the utility operator does not need to start another generator immediately when loads increase, then the energy storage system should be located at the power station.

When the energy storage system is to be used for smoothing the available power from a particular renewable energy generator, also known as capacity firming, then the energy storage system shall be located at the site of the renewable energy generator.

When the renewable energy generators include many individual systems geographically dispersed across the whole distribution network (e.g. building roof tops etc.) then energy storage systems being used as generation reserve for supporting the renewable generation could then be centrally located, such as at the power station. This type of system could then be sized to act as a form of “spinning” reserve such that when the renewable generation is low in output, e.g. clouds covering all the solar systems on the island for the rest of the day, then the energy storage “spinning” reserve allows time for the operator to bring other generation capacity on line.

4.3 Power Rate Limit (Power Ramping)

The energy storage system must be located with the renewable energy system when it is providing the power rate limit. Depending on the configuration it could be the energy storage inverter or the renewable energy grid connected inverter that performs this function.

For wind farms it would be the energy storage system inverter.

For solar systems it could be either the energy storage inverter or the grid connected inverter subject to the configuration. For a solar system:

- In a dc coupled system it would be the PV grid connect inverter that controls the ramp rate.
- In an ac coupled system it would be the control system monitoring the PV inverter and controlling the energy storage system inverter to provide the ramping power down and the PV inverter controlling the ramping power up.

The need for ramp rate control is dependent on the dispersity of the renewable energy generator sources throughout the grid network. If there are only a few very large solar systems (utility scale solar farms) connected to the grid then this will typically need ramp rate control. If there are distributed solar systems in many locations across the whole distribution network (e.g. solar on building roof tops) then it has been shown in many studies that the effect of cloud cover is reduced because some systems are being shaded while others systems are coming out of the shade of the cloud. The overall net effect is that there might be a total capacity across the grid of 1MW of solar however perhaps only 600kW is delivered at any one time. It is only when the cloud cover is such that all systems are being shaded and stay shaded for the rest of the day that the operators then needs to use the storage as “spinning” reserve to provide the time needed to start extra generation capacity. (See section 4.2)

4.4 Storage of Excess Renewable Energy

The energy storage system generally should be located at the renewable energy site when it is storing excess renewable energy. Having it at another location may incur too many losses between the generation and the storage.

If the output of the solar power system is being curtailed at a specified maximum power input to the grid, then the system configuration must be dc coupled or at least include a dc coupled component for the excess solar is to be stored in the batteries. If the configuration is all ac coupled, the grid connected inverter will not be able to supply the excess solar power as ac power to the energy storage inverter for it to use that excess power in charging the batteries.

In an ac configuration that is not being curtailed at a specified maximum power input, the use of excess solar power for charging the energy storage device would then be controlled by the automated control system or by the operator signaling the energy storage inverter to act as a charger thereby storing the excess solar energy in the energy storage device.

4.5 Peak Demand Lopping or Peak Shaving

When the energy storage system is being used for peak demand lopping (also known as peak shaving) the location of the energy storage depends on the main charging source of the energy storage system. If the main charging source is renewables, then locating the energy storage systems with the renewables would probably be the most efficient use of the system. If the main charging source is the existing fuel generators at the power station, then that would probably be the most efficient location.

Due to the availability of land, the exact geographical location of the renewable energy system in the distribution network may be away from the major loads during the peak demand period. In this situation it may be best locating the energy storage systems at the power station or at a location close to the peak loads if they are geographically concentrated (e.g. an industrial facility that has a high load at a particular time of day).

4.6 Facilitate no Fuel Generators Operating in Daytime

If the renewable energy system, often solar, is one large system then the energy storage system should be located near that system since the solar systems and the energy storage system will work closely together. However, when there are a number of renewable energy systems dispersed around the grid then to be most effective, the energy storage system will need to be large enough to work in parallel with all the renewable energy generators. In this scenario the energy storage system should usually be located at the main power station. The energy storage system can then be used as the grid forming device taking the place of fuel generators.

4.7 End of Grid Support

As the name suggest, the energy storage system will need to be located at the end of the grid where the voltage support is required.

4.8 Reactive Power Support

Poor power factor happens in the distribution network due the many inductive loads that are connected to the grid. For this reason, all power factor correction devices are located throughout the distribution network, usually very near the loads causing power factor problems.

When the reactive power is required as a result of the renewable energy generation not being able to provide reactive power, e.g. solar power supplying real power only (power factor=1), then the energy storage system that is providing the reactive power must be located at the site of the renewable energy generation.

5. Size of Energy Storage System Required

The electrical specifications of an energy storage systems will be defined in relation to the peak power rating in kilowatts (kW) of its inverter and the capacity of the energy storage in kilowatt-hours (kWh). The rating of the inverter will be selected whilst considering the following criteria in relation to the requirements of the specific purpose of the storage:

- The peak power rating of the renewable energy generation linked to the energy storage system.
- The peak power rating of all the renewable energy generation connected to the grid.
- The total load power that shall be supplied by the energy storage system for peak lopping.
- The maximum demand on the whole grid.
- The maximum demand on the feeder at the end of grid.

The energy storage capacity will be dependent upon the actual application of the energy storage system.

Note: This section of the guideline is only relating to solar power systems, not wind systems. The guideline will be updated in the future to cover wind power systems.

5.1 Rating of Inverter

5.1.1 Based on peak power rating of the renewable generator linked to the energy storage system

Does the energy storage inverter power need to be the same power rating as the peak power of the solar array? In practice, the grid connected PV inverter does not need to the same rating as the peak power of the solar array. The fact that the solar power output is dependent on the available irradiance and that there are module power losses due to temperature and transmission power losses between the array and the inverter, the power rating of grid connected PV inverter is often less than the peak rating of the of the solar array.

Therefore, the power rating of the energy storage inverter needs to relate to power rating of the solar inverter.

The energy storage inverter should have the same output power rating as the solar inverter when the energy storage system is being used for any of the following:

- grid stability;
- capacity firming (smoothing);
- spinning reserve based on the size of solar system.
- power ramping

Whether it needs to have the exact same rating is debatable since it is unlikely that in a cloud cover event the solar array power output would decrease to zero and also the solar power output would only be at its maximum output (if at all) for a short period of the day. However, to be conservative it is best to design that both inverters are the same size.

If the energy storage system is being used for solar energy excess storage, then theoretically the power rating of the storage inverter would be based on the power rating of the available excess. In practice an energy storage system on the grid is unlikely to be installed just for absorbing the energy excess. Though storage of excess renewable energy may be included in the function of the storage, the energy storage inverter rating should be based on the main reason why the energy storage system is being installed.
If both the solar array and energy storage system are new and the inverter being used is a hybrid inverter that connects to both the solar array and the energy storage system, then the hybrid inverter would be sized similarly to how a grid connected inverter is sized. That is, somewhere between 85% and 100% of the peak solar rating depending on the type of modules and possibly the location and orientation of the array.

Note: Sometimes the PV inverter power rating is based on the maximum solar power allowed to be supplied to the grid. That is the solar power may be curtailed to the value of the inverter's capacity. Often with these types of systems the rating of the PV array can be up to 50% greater than the rating of the inverter. This may be done so that the maximum allowed solar power being supplied to the grid is available for a longer period of time during the day.

5.1.2 Based on total peak power of renewable generation connected to the grid

Where the solar systems are geographically dispersed around the grid network then the energy storage system should not be sized based the output of one solar system. As stated previously, in this situation energy storage to facilitate grid stability and smoothing would best be located at a main power station. Determining the optimum power rating of the energy storage will be more difficult when multiple solar installations are on the grid.

Firstly, the actual total peak rating of each of the solar systems should be determined. Any data available that provides information on the typical total power profile of the solar systems onto the grid is needed to determine what type of fluctuations in solar generation have been observed. Any energy storage system that is required should be based on the actual technical issues the utility operator is having as a result of these dispersed solar systems.

One possibility could be that the technical issues have resulted from a section or sections of the grid where there is a high penetration of solar systems. The energy storage system could then be sized based on the maximum power rating of the solar systems in that section (or sections) and the energy storage system located in that section (or sections) of the grid.

In practice, thus far there have only been a few countries in the Pacific islands that have allowed numerous privately owned solar systems to be installed. These countries typically also have large utility owned solar systems or those supplied and owned by independent power producers. Any technical issues being seen in the grid could be overcome by just installing storage systems at near the existing (or proposed) large solar systems. The power rating of the energy storage inverter could then be determined as per section 5.1.1

5.1.3 The total load that should be supplied by the energy storage system for peak lopping

If the energy storage system is being used for peak lopping, then the energy storage inverter would need a power rating equivalent to the amount of peak power demand that is being delivered by the storage. Referring to Figure 4 as an example, approximately a 400kW inverter would be required in that case.

5.1.4 The maximum demand on the grid

If the long term objective is to have times during the day where the utility fuel generators are not operating and the required power is being supplied by the solar system and energy storage system then the power rating of the energy storage inverter will need to be, as a minimum, the maximum power demand of the grid during the period of the day when the storage and associated solar is the solar power source. In reality it would have an oversize factor based on the standard oversize factor used by the utility when selecting what fuel generators sets are required to meet the maximum demand.

5.2 Energy capacity of energy storage system

5.2.1 Grid stability – frequency and voltage support

When the energy storage system is to provide frequency regulation then the storage is only required for a short period of time. Some systems have their full power delivery set as low as 15 minutes. As an example, if the inverter is rated at 1MW then the energy storage would be 250kWh to provide the 15 minutes of frequency stabilisation energy.

Similarly, for voltage support only a short time would only be required.

Note: Depending on the type of energy storage system it is important to ensure, particularly when using batteries, that for the required time period, the energy storage system is able to provide, the current that is drawn when the inverter is providing maximum power.

5.2.2 Spinning reserve, smoothing and capacity firming

When the energy storage system is only to provide spinning reserve then the amount of storage required is based on the length of time it would take for the utility operator to start another generating source and bring it online to the grid.

Systems that are typically being installed currently for smoothing and capacity firming are using 1 hour of storage. As an example, if the inverter is rated at 1MW then the energy storage would need to be 1MWh

5.2.3 Power rate limit (power ramping)

When the energy storage system is being used for power ramping then the amount of storage required is determined using the specified ramp rate.

The simplest calculation would be to multiply the inverter rating by the length of time for the ramp.

Worked Example 3

Assume the solar array output is that of the Energy Storage inverter of 1MW.
The down ramp rate on the inverter has been set at 8.3% per minute.

The total time to go from 100% (1MW) to 0% (0W) 100/8.3 = 12 minutes = 0.2 hours (12/60)
So the energy required based on the simple calculation would be 0.2hrs x 1MW/2 = 0.1MWh (100kWh) as displayed in Figure 8

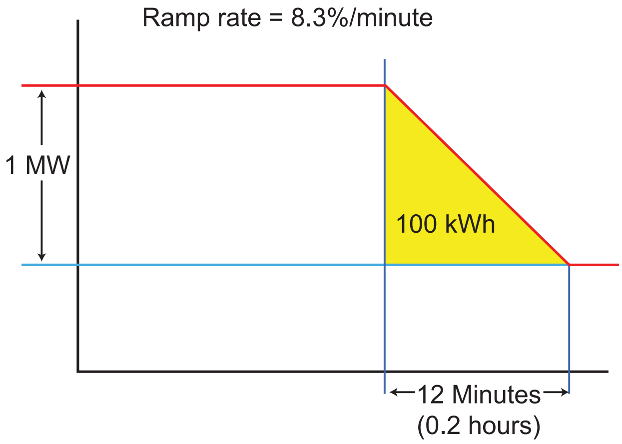

Figure 8: Energy Storage Required

A more detailed calculation would be based on determining the actual energy required for a short time period, e.g. each minute, and then adding the total energy for all the time periods.

Worked Example 4

Assume the solar array output is that of the Energy Storage inverter of 1MW.
The down ramp rate on the inverter has been set at 8.3% per minute.
8.3% x 1MW per minute = 0.083MW per minute.
The following table shows the power and hence required per minute.

End of Minute	MW	Time (Hrs)	MWh
0	1	0.0167	0.0167
1	0.917	0.0167	0.0153
2	0.833	0.0167	0.0139
3	0.750	0.0167	0.0125
4	0.667	0.0167	0.0111
5	0.583	0.0167	0.0097
6	0.500	0.0167	0.0083
7	0.417	0.0167	0.0069
8	0.333	0.0167	0.0056
9	0.250	0.0167	0.0042
10	0.167	0.0167	0.0028
11	0.083	0.0167	0.0014
12	0	0.0167	0
	Total		**0.1083**

So from detailed analysis the required energy storage is 0.1083MWh (108.3kWh)

In reality the energy storage system will generally be required for other reasons, e.g. smoothing . In that case it is likely that the energy storage capacity will be based on that determined in 5.2.2, that is a 1 hour minimum. However, if the final determining factor for the required energy storage capacity is ramp rate time, then consideration must be given to the time it will take for the energy storage system to be recharged in case it is required again.

5.2.4 Storage of Excess Renewable Energy

Determining the amount of energy storage required for storing the excess renewable energy generated will require an interval analysis study to determine the amount of excess renewable energy there would be each day. The analysis would compare the total available solar power (and hence energy over time) compared with the load power at the same time (and hence energy over time). Based on the amount of excess energy calculated, the storage system would then need to be sized to be able to store all that excess renewable energy.

5.2.5 Peak demand lopping or peak shaving

Determining the amount of energy storage required for peak demand lopping will require the utility to state what they specify as the peak demand for their grid. This would be based on the size of existing fuel generation and at what stage they require an extra generating unit to come online to meet the peak energy demand. The amount of energy to be supplied by the energy storage system would therefore equal the amount of extra energy that is technically supplied by the peak demand generator when it is operating.

5.2.6 Facilitate no fuel generators operating in day time

As a minimum, the energy storage system would need the energy capacity to provide the required power that is in excess of the power (and loads) being supplied by the PV systems (s) for the hours that the fuel generators will not be operating. The energy storage system will also require sufficient capacity to provide the smoothing, that is capacity firming, due to the intermittency of the solar power. Though the energy storage system can also be charged by the fuel generators when operating during the night, that is quite costly due to the fuel needed and the losses incurred, so the solar array should be sized that it can also provide some of the extra day time charging to the energy storage system. Therefore, the solar systems power rating and associated inverter would need to be greater than the recorded daytime maximum power demand to allow for energy storage charging. In this scenario the energy storage inverter can still be rated to meet the maximum demand power however the energy capacity should have a minimum ratio of 1kWh of storage capacity for each 1kW of peak solar power.

5.2.7 End of grid support

This is for voltage support and 1 hour of storage would be sufficient based on the size of the selected inverter to provide the support to the distribution feeder.

6. Types of Energy Storage

The energy storage technologies available for utility-scale grid storage have different properties and the technical suitability of each has to be assessed for the type of grid service required. For example, for enhanced frequency regulation provision due to an increase in RE grid penetration, flywheel storage could be an option considering that flywheels can deliver high power within seconds. Most battery technologies, such as Lithium-ion or Lead-acid, can also be used for this purpose and integrating such battery technologies with flywheels could have better economic benefits and well-suit the grid application. The power and energy relationship as shown in figure 9 below play an important role in being chosen for various grid services based upon technical grounds. Though this figure shows clear distinctions among the storage technologies, the rapid developments in storage technologies may well lead to overlapping of the power and energy attributes of these technologies between different applications.

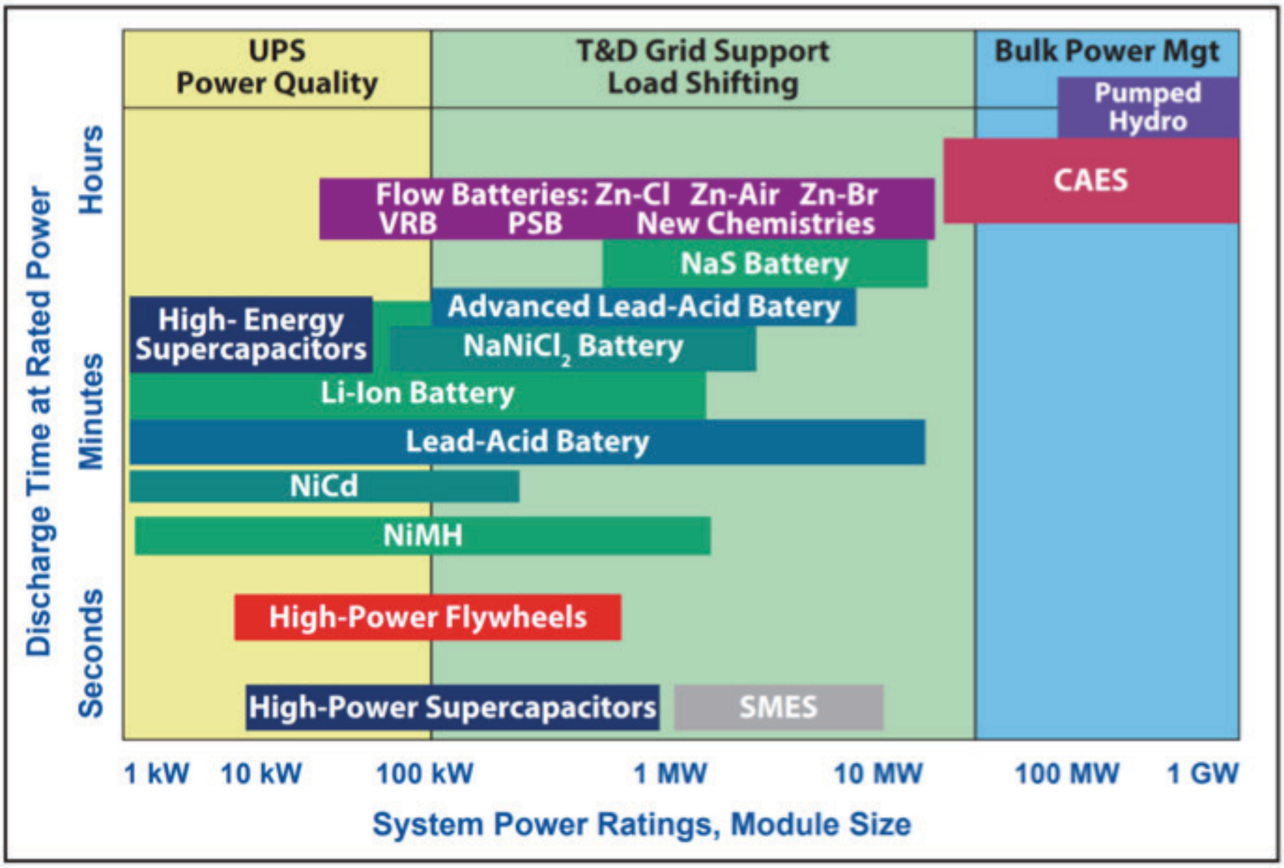

Figure 9: Energy Storage technologies positioned as per their power ratings and discharge times at rated power. Source: IRENA (2017), Electricity Storage and Renewables: Costs and Markets to 2030

6.1 Lead Acid batteries

Lead acid batteries are electrochemical batteries where electrical energy generated by an energy source is converted and stored as chemical energy. This is then converted back to electrical energy when required. Lead acid battery technology is the most mature electrochemical technology in the current market with high operational experience. They are of two main types – Valve-Regulated (VRLA), sometimes referred to as Sealed Lead Acid batteries, and Flooded Lead Acid batteries. The most commonly used lead acid battery type for grid-scale energy storage is the VRLA batteries though older installations have successfully used flooded batteries. The abundant production, knowledge, experience and supply of these batteries have made them cheaper compared to most other battery technologies currently available.

They have been demonstrated as successful for services like capacity firming and load shifting through projects commissioned in the United States[1] and Vanuatu[2] . The VRLA battery technology is often referred to as 'Maintenance free' battery technology as it doesn't require frequent maintenance – either to check electrolyte level, acid spillage or gas ventilation as they are all regulated and remain sealed when the battery is operated properly. It does also mean that the in the event of uncontrolled overcharge, the batteries cannot be maintained (topped up with water) to bring them back to a serviceable storage device. This means that the lead acid batteries could have relatively less maintenance costs involved but if damaged due to improper service, they cannot be repaired. They are particularly sensitive to overcharging and high quality charge control systems are essential. The recycling options available for these batteries are economical and dominant in the recycling industry so that up to 98% of the battery can be recycled.

BEWAG utility in Berlin, Germany had a 17MW/14MWh Lead acid battery storage installed which was commissioned in 1986 and de-commissioned in 1995 after it's end of life-term. This installation was built to provide for "spinning" reserve and frequency regulation. It replaced the previously existing turbo-generator. The battery storage system was able to ramp up a minimum of 5MW per second whereas the turbo-generator it replaced had a power gradient of only 4.5MW per second.

The Southern California Edison (SCE) utility in California, US commissioned a 10MW/40MWh Exide deep-discharge Lead acid battery storage system in 1988. It was used for grid services like peak shaving, load levelling, load following, spinning reserve, transmission line support, voltage and frequency control and black-starts before it was de-commissioned in 1997 at the end of its life-term.

Apart from these advantages there are more disadvantages that restrict their uses only to automobiles or small-scale energy storage. These batteries have low energy density, meaning a large number of battery cells are required for storage compared to some other battery technologies. This battery's chemistry limits the usable capacity, also known as depth of discharge (DOD), increasing the need for more and/or higher capacity cells to avoid damage to discharge levels that are too great. The logistics of these batteries itself also poses a large capital barrier for grid storage implementation as they are very heavy and relatively fragile. Lead acid batteries have a low cycle life when discharged deeply, however continuous research for increasing the cycle life is being undertaken which could pose an advantage for grid storage in the near future. Advanced lead acid batteries addressed later in this

[1] *http://www.energystorageexchange.org/projects/1419; http://www.energystorageexchange.org/projects/1788*
[2] *http://www.energystorageexchange.org/projects/2202*

Lead Acid batteries loose capacity at very low temperatures and at high temperatures the cycle life decreases. Apart from these, lead acid battery technology has another factor, sulfation, where during numerous charge and discharge cycles not all of the active materials can be reconverted resulting in a gradual loss of capacity. This decreases their cycle life further if there is inadequate maintenance. The grid energy stored may have to be discharged frequently to smooth the renewable intermittency in the electric grid. Hence the batteries may be required to be operated long periods at Partial State of Charge (PSoC), which will affect Lead acid battery life through irreversible sulfation.

These disadvantages have led to Lead Acid battery technology not being the most appropriate option for utility-scale grid energy storage today. Due to increased market competition, this technology is being rapidly displaced by other battery storage solutions like Lithium-ion and flow batteries. The cost, however, tends to be lower than other battery options, particularly for smaller installations. The energy installation costs of this technology currently stands at $105 to $475 USD/kWh and it is forecasted by IRENA[3] to decline further to $50-240 USD/kWh by 2030.

6.2 Lithium-ion Batteries

Lithium- ion batteries are the dominant technology for utility-scale grid storage. They have been demonstrated successfully for grid services including capacity firming, frequency and voltage regulation and grid power quality enhancement. A range of combinations of materials has led to different Lithium-on battery chemistries including Lithium-Iron-Phosphate (LFP), Lithium Nickel Cobalt Aluminium (NCA), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Manganese Oxide (LMO), and Lithium Titanate Oxide (LTO). Considering attributes such as safety, cost, power and energy performance and cycle life, the most commonly used Lithium ion technologies are Lithium Iron Phosphate (LFP) and Lithium Nickel Cobalt Aluminium (NCA).

Li-ion battery technology has many advantages, such as relatively high specific energy, high energy and power densities and higher cycle lives than traditional lead-acid batteries. They can also be built to have a high charge and power discharge capability, thus making rapid charging and discharging viable. This technology is best suited for short term discharges making them an appropriate solution for frequency regulation and enhancing power quality of the grid. In addition to these, the technology has an excellent roundtrip efficiency of about 90-96% and a low self-discharge rate. With decreasing costs of the technology, Lithium ion battery energy storage systems are becoming an economical option for grid energy storage.

However, there are a few issues associated with this technology, such as thermal stability and safety. These batteries can also produce large fault currents due to higher cell voltage and low internal resistance. Thermal runaway, an attribute common to the Lithium-ion battery technology, causes chemical reactions that release oxygen when lithium metal oxide cathodes overheat and also increases the cell fault current. These may lead to the Li-ion cell catching fire. This issue apart from the internal chemistry can also be caused by external stimuli which can be non-design related such as external heat conditions, over-charging or discharging or high current charging. The operating temperature also plays a role in the battery's performance and life cycle. For example, an increase of over 10˚C greater than the optimal operating design temperature of a Lithium-ion battery can reduce the lifetime of the cell by 50%. These batteries require a standard operating temperature between 20˚C and 30˚C in order to record their best

[3] IRENA Oct 2017 - *Electricity Storage And Renewables: Costs And Markets To 2030*

performance. Hence, Lithium ion battery systems always should be supplied with integrated thermal management and monitoring systems called a Battery Management System (BMS), and much research and effort is focused in this area. The BMSs are tailored by the manufacturer based on the cell chemistries and corresponding attributes and also designed to communicate the state of charge of each cell to the battery inverter/charger.

Tesla, Bosch, Samsung, Exide, and LG are some of the major market players in the Lithium-ion battery technologies. The energy installation costs of this technology is currently estimated at between $200 to $1260 USD/kWh[4].

6.3 Capacitors and Ultra-Capacitors

Capacitors are a storage technology where energy is stored in an electric field rather than being a chemical reaction in the battery technologies. Conventional capacitors are used in a variety of ways in electronic devices, such as temporary storage, power or signal filtering. The technologies used are highly dependent on the reason for their use. The technology used in conventional capacitors is not well suited to large scale energy storage.

Supercapacitors or ultra-capacitors have been under development for many years and are now entering the market place as technically viable solutions that have about 10 to 100 times larger energy storage capability than a conventional capacitor.

Ultra-capacitors can be charged very rapidly and used to provide a large amount of power for a very short time. This technology can have 10 to 100 times higher power density than any rechargeable battery technology. The ultra-capacitor can also tolerate a high number of charge and discharge cycles and this rapid charge/discharge cycle doesn’t reduce the capacitor’s lifetime. This technology is claimed to last about a million cycles but as there is limited field data and lifetimes are based upon manufacturers datasheets as 10 to 15 years. These lifetimes have been tested with the worst operating conditions for accelerated lifetime testing but significant real-time field testing is not readily available. Their very low internal resistance also means that the system doesn’t overheat due to rapid or continuous charge/discharge cycles thereby having reduced maintenance costs and lower losses.

Ultra-capacitor technology that can discharge energy within milliseconds can be used mainly for voltage and frequency stabilization. This is due to their very high power to weight ratio as mentioned above. This technology is more advantageous when incorporated as a combination with other conventional battery technologies like lead-acid or lithium-ion batteries. This combination of technology has added advantages which are further discussed in 6.4 of this guideline.

6.4 Batteries with Capacitors

Conventional lead-acid and lithium-ion battery technologies have been combined with ultra-capacitor technology resulting in hybrid energy storage technologies that have the combined advantages of both technologies and very few added disadvantages. For example, the comparatively lower power density attribute of the Lead-acid battery is improved when combined with ultra-capacitor technology mainly due to the presence of the carbon electrode which enhances the storage system’s performance.

6.4.1 Advanced Lead-Acid Batteries

Advanced lead-acid battery technology combines advantages of lead-acid battery technology with ultra-capacitor technology. This is a promising technology which has already been implemented in Australia, Japan and U.S.A and has been proven successful for various grid services like frequency regulation, power quality and grid support, smoothing of RE penetration, load shifting, providing spinning reserve, and ramp-rate control. The advantages of lead-acid batteries such as a high energy density when combined with ultra-capacitor's benefits of high power density and long cycle life paves way for efficiently supporting the grid services mentioned above.

One of the Advanced Lead Acid battery technologies is the Ultrabattery that was invented by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO)[4] . The Ultrabattery significantly reduces various disadvantages of the Lead acid battery technology. It has comparatively high capacity throughput compared to a standard VRLA battery. Tests have proven to record more than 4 times capacity turnover than a conventional best-performing VRLA battery. It allows more rapid charge/discharge cycles than a VRLA battery over its lifetime and needs much less frequent replacement. The Ultrabattery has a very high round-trip efficiency of about 93-95% when performing grid regulation services and about 86-95% efficiency when performing energy-shifting services including ramp rate RE smoothing operations in Partial SoC (PSoC) conditions. The VRLA battery when discharged under the same conditions would be able to operate only at an efficiency of about 70%. The major drawback of the traditional lead-acid battery technology is sulfation due to frequent charge and discharge at PSoC conditions. To prevent the sulfation from becoming permanent, the Lead acid battery has be over-charged at periodic intervals (equalization charging) for desulfation to occur. This is not required in an Ultrabattery as it can perform at high efficiency in a PSoC regime without requiring periodic overcharging.

But the advanced lead-acid battery technology still uses lead which is a toxic material and there are environmental concerns associated with it. It still has lower energy density compared to newer technologies like Lithium-ion, Advanced Lithium ion or Flow batteries and requires a larger number of cells compared to other battery storage technologies.

6.4.2 Advanced Lithium-ion Batteries

Lithium-ion batteries are currently the most beneficial choice in terms of both technology and economy for utility scale grid energy storage. The main benefit for this choice over other energy storage battery technologies is that it has high energy density, meaning the weight of these cells and the number of battery cells required is reduced. Unfortunately higher energy density can also include a catastrophic risk of battery fire. This safety risk of the Lithium-ion batteries have pushed for further research and development of advanced lithium-ion battery technology which combines various materials and technologies and not all final products have reached the mass production stage. Lithium-ion capacitors are one such technology that have already been implemented and this is similar to the advanced lead-acid battery which incorporates ultra-capacitor technology.

Lithium-ion capacitor technology has been determined to have about 4 times higher energy density than a capacitor but lower than a Lithium-ion battery. This feature makes the Lithium-ion capacitor safer than Lithium-ion batteries as the thermal runaway is significantly reduced.. This technology can discharge within seconds without damage. The lithium-ion capacitor has greater cycle life than Lithium-ion batteries and is intended to maintain over 90% of its initial capacity after 100,000 cycles . The high ramp rate and fast response capability of the Lithium-ion capacitor combined with its high energy density can be used for grid services like smoothing PV fluctuations in the electric power grid, capacity firming, and load levelling/balancing.

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[4] *http://ultrabattery.com/wp-content/uploads/sites/2/2013/04/Ecoult_-Integrating-Renewables-into-the-Grid_FINAL.pdf*

6.5 Nickel based Batteries

6.5.1 Nickel Cadmium (Ni-Cd) Batteries

Nickel-cadmium (Ni-Cd) battery technology was once considered to be more advantageous than any other battery technology. With advances in energy storage systems, Nickel-Cadmium battery technology lost its dominance in energy storage technologies. It has high energy density, greater than lead acid battery and has a high discharge rate that can prove useful for grid frequency control and increase PV grid penetration by smoothing the power generated. It also has a greater lifetime with better temperature performance than lead-acid batteries. But when compared to new battery technologies, Ni-Cd batteries have huge disadvantages such as lower energy density, use of toxic materials, a high self-discharge rate which could be at the rate of 10% per month at 20˚C and sometimes higher at higher temperatures. These batteries are vented, meaning that they produce hydrogen gas during gassing and hence require proper ventilated enclosures to reduce hydrogen build-up.

This battery chemistry is being replaced by Nickel-Metal Hydride batteries and Lithium-ion battery technologies mainly because of the use of very toxic materials in the Ni-Cd battery. This restricts the use of Nickel-based batteries for grid energy storage applications. Further developments to replace the toxic cadmium component has resulted in various other battery chemistries such as Nickel-Metal hydride, Nickel-Iron, Nickel-Zinc and Nickel-Hydrogen. When factoring in the recycling costs of toxic Cadmium in the battery, it increases lifecycle costs making it less attractive for utility-scale battery systems. But currently these are being replaced by Lithium-ion battery technology due to the latter's advantages and costs.

6.5.2 Nickel Metal Hydride (NiMH) Batteries

Nickel Metal Hydride batteries do not use toxic cadmium in its chemistry but still share a few attributes with the Ni-Cd battery. These batteries are generally sealed and hazards due to improper ventilation are significantly reduced. NiMH batteries are more reliable than the Ni-Cd batteries due to their having higher capacity and longer cycle life when operated under manufacturer recommended conditions. Though they have a higher energy density (75Wh/kg) than Ni-Cd batteries (55Wh/kg), NiMH batteries have a higher self-discharge rate of about 30% per month.

With the rapid development in the other battery technologies, the Ni-based batteries are being bypassed by the choice of better and cheaper battery systems like Lithium-ion storage systems.

6.6 Flow Batteries

A redox Flow battery is an electrochemical battery technology, but is completely different from other battery technologies, as these have two chemical components dissolved in electrolyte solutions and stored in tanks separated by a membrane. In this membrane, which is the reaction unit, reversible electrochemical reactions occur when the electrolytes are pumped through it and these reactions constitute the charging and discharging of batteries. The most mature redox flow battery technologies in the market are the Vanadium Redox Battery Energy System and the Zinc Bromine Flow battery.

Flow batteries have many advantages over other rechargeable batteries including: flexible power and energy scalability through design of the cell stack membrane and the electrolyte storage volume tanks; a cycle life of more than 10,000 cycles[5]; abundant raw material availability making the technology cheaper with energy installation costs between $315 USD/kWh and $1680 USD/kWh; high usable capacity unlike lead acid batteries; thermal runaway prevention during flow of electrolytes hence making it safer than

[5] *https://web.archive.org/web/20110823150247/http://www.jsrmicro.be/en/lic*

other electrochemical battery technologies and easy operation. They have negligible degradation with the possibility of unlimited longevity. However, these batteries have a relatively low conversion efficiency (85%) and high maintenance complexities and costs associated mainly due to pumps, sensors, and sophisticated flow management mechanisms. The tanks may also require additional safety in the design stage to avoid electrolyte leakage in the site during long-term operation. Due to their operating temperature restrictions from 10˚C to 40˚C, the energy density of this battery technology is only about 25Wh/L.

The Zinc-bromine flow battery uses a hybrid flow battery technology. This type of battery system has two tanks of zinc bromide electrolyte solutions and during charging or discharging of the battery these solutions are pumped through a reactor stack and into the tanks. It has one material not fully soluble in the electrolyte solution of zinc bromide. The Pacific islands do not currently have a utility-scale Flow battery installed for grid storage, but Tahitian[6] French Polynesia has a 2000kWh Zinc-bromine Flow battery system (ZBB Enerstore) installed with a 896kW PV system for a microgrid in a luxury eco-resort.

Flow batteries are usually preferred for large scale grid storage applications. These batteries can provide for load balancing and peak shaving for which their energy and power densities can be designed as mentioned above. Recent developments in integrated battery system solutions like Redflow's Large Scale Battery[7] is promising as it enhances ease of installation of batteries on the grid. This plug-and-play integrated battery-inverter system has provision of installation of up to 45 zinc-bromine flow 10kWh batteries connected and 6 Victron Quattro 12kW 48/15000 battery inverter/chargers in a six-metre (20-foot) shipping container. These can be tailor-fit for each deployment depending on the grid application requirement. Multiple numbers of such containers can be deployed as per the energy storage requirement on the grid.

6.7 Sodium-Ion Battery

Sodium-ion batteries (SIB) operate in a similar way to lithium-ion batteries. The electrolyte is sodium sulfate in an aqueous solution. The main advantage of the sodium ion battery is that there are no harmful chemicals that must be disposed of at the end of their life and that they can 100% discharged in every cycle. They also have high cycle life in excess of 6000 cycles when discharged by/to 50%. The abundant availability and low cost of sodium compared to Lithium has been the significant reason for sodium-ion battery technology's push into the energy storage market.

The main disadvantage is that sodium-ion batteries have a much lower energy density (90Wh/kg) and higher internal impedance than lead-acid and lithium-ion batteries. This means that a larger area (compared to lead-acid and lithium-ion batteries) is required for the same amount of energy stored or for a specified energy. Also their surge current capability is less than that of lead-acid and lithium-ion batteries. Currently the applications of sodium-ion batteries are limited to stationary energy applications where energy density is not paramount, and where the electrical load is essentially constant.

6.8 Sodium Sulphur (NaS) battery

A Sodium Sulphur battery is a high temperature battery which is constructed using liquid active materials and a solid ceramic electrolyte. A high temperature of the range of 300˚C to 350˚C (570˚F to 660˚F) is required to maintain the active materials of the battery in liquid state. This technology has been widely used in Japan for grid storage services such as load levelling at wind farms and has been demonstrated to be a successful technology with more than 300MW of this battery storage system is installed in Japan.

[6] http://www.energystorageexchange.org/projects/1038
[7] https://redflow.com/products/redflow-zbm2/redflow-lsb/

NaS batteries have been installed at a large-scale and sufficient operational experience can be gained from projects in Japan alone. These batteries have a self-discharge rate of up to 0.05% or 1% per day, but this depends on the location and its application. They have higher energy densities than flow batteries and lead acid batteries. It is currently built to have energy densities between 140Wh/L and 300Wh/L reducing the footprint required for battery systems installation. Due to their high energy density they can be used as capacity reserve and provide for load shifting in the electrical grid. These batteries can operate efficiently for 5000 cycles although a few reports indicate a more than 10,000 cycle life possibility. The materials used in this battery technology are non-toxic and have a 99% recyclability rate.

The high temperature operation of the battery requires a suitable thermal enclosure and electrical heater. If the battery is not charged or discharged frequently, that is, if it is not operated effectively, then it will require further energy to maintain its high operating temperature. This need for high temperature maintenance of the battery is a disadvantage as it increases the system operation and maintenance cost. The operating cost alone is estimated to be between $40 and $70 USD/kWh per annum. This battery technology also suffers from corrosion in the long-run and reduction in cost comes with developing robust materials, coatings and joints that will withstand the constant heat and increase the battery lifetime. The cost of Sodium Sulphur battery technology varies between $263 USD/kWh to $735 USD/kWh.

6.9 Pumped storage Hydroelectric System

Pumped Hydropower or Pumped Storage Hydroelectricity system is the most widely deployed type of energy storage system with at least 165GW of operational systems accounting for about 96% of energy storage installations in the world. It is the oldest form of energy storage and has been in active use since the 1890s. Like Lead-acid battery technology, this energy storage system also has extensive operational experience. The system requires two water reservoirs located at different altitudes. It works by initially pumping water from a lower reservoir to an upper reservoir using energy during low demand or when there is excess generated power. During times of high energy demand, water stored in the form of gravitational potential energy in the upper reservoir is released back into the lower reservoir through a pump / turbine unit attached to a reversible electric generator/motor system. This generated electricity is then fed into the electric power grid.

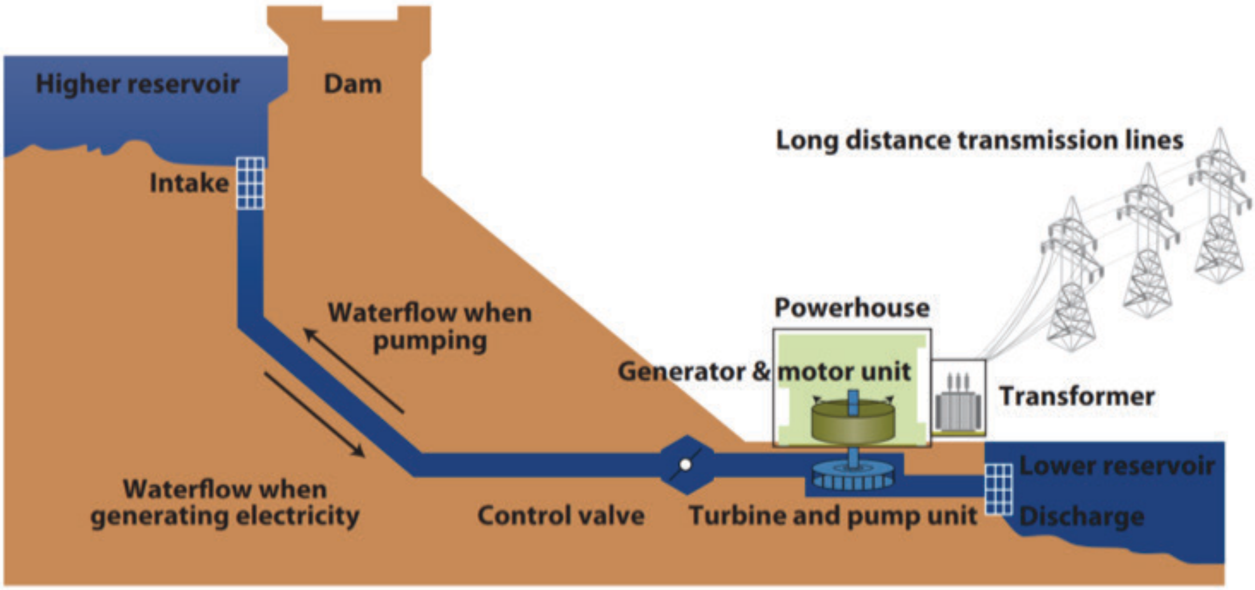

Figure 10: Pumped Storage Hydro System.
Source: IRENA (2017), Electricity Storage and Renewables: Costs and Markets to 2030

The round-trip efficiency of the pumped storage hydroelectric system after taking into account the water evaporation is about 70%-84%[8]. Research and demonstrations to increase the efficiency of these pump-back hydroelectric dams that generate electricity by first pumping water from a lower to upper reservoir are being undertaken. The primary materials required for constructing a pumped storage hydro plant are concrete and steel and these materials can last for more than 50 years. Appropriate maintenance of the turbine/generators along with few renovations can increase the lifetime of this storage system to up to 100 years. This technology can store energy for days providing there is a long-term storage solution and has a very low cost of storage. The energy density of this storage system is very low of the order of only 2Wh/L, thus requiring a large storage volume. There are also some environmental concerns associated with this technology where flora and fauna in and around the system's area could be affected and this might be restricted in some jurisdictions. Apart from these disadvantages, the payback period is very long owing to very high initial capital investments and long construction times.

The energy that can be stored depends on the volume of the reservoir and the height of the surface of the upper pond relative to the surface of the lower pond. Hence this storage system has strict geographic restrictions. Using the ocean as the lower reservoir has been demonstrated to be successful in Japan through the *Okinawa Yanbaru Seawater Pumped Storage Power Station* project. This saves significant lower reservoir construction cost, however maintenance cost of penstocks and turbines may increase due to seawater corrosion and the upper pond must be sealed against leakage into the ground if groundwater salt contamination is to be avoided.

This technology has been used mainly for load levelling/balancing i.e. to provide for energy demand when there is shortage of energy generated from the base-load power plants. It also can be used as a synchronous condenser to provide for frequency regulation when it is neither generating nor pumping water. Dinorwig pumped-storage hydro-electric power plant in United Kingdom for example, has been providing frequency regulation support to the national grid by spinning the turbine-generator in air i.e. in synchronous condenser mode and it is able to ramp up from 0 to 1320MW in 12 seconds.

Pumped storage will only be practical at a few sites in the Pacific island countries.

6.10 Flywheel

Flywheels employ mechanical storage technology wherein energy is stored as rotational kinetic energy by accelerating and braking a heavy spinning disc. Energy is stored in the flywheel machine by increasing its rotational speed at times there is off peak energy or when excess energy is being generated. This spinning disc is built around a fixed axis/flywheel rotor that is connected to a dual function electric machine that acts as a motor during charging and storing energy in the flywheel and as a generator during energy discharge. The energy stored is proportional to the speed of rotation with the maximum speed dependent on the stress restrictions of the material in use. The materials should be strong and be able to resist large centrifugal forces, hence as the requirement for energy storage capability increases, the cost significantly increases.

Flywheels have very high power density of up to about 10kW/L with very fast response times, sometimes within 10 milliseconds. Hence they have been used for short-term energy storage as a spinning reserve for frequency regulations, peak power offsetting and to smooth out fluctuations due to increased RE penetration. Flywheels have a very long lifetime of about 25 years with outstanding cycle life of up to 1 million cycles. With a very high energy installation cost of $1500 to $6000 USD/kWh and high loss rates of up to 15% per hour, these are employed only for short-term grid storage purposes. They can be integrated with other medium or long-term energy storage solutions like batteries, to provide added grid support like capacity firming and load shifting.

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[8] *https://www.sciencedirect.com/science/article/pii/S2352152X17304437#sec0010*

Flywheel storage is primarily used for frequency regulation – i.e. to improve power quality; offset power peaks; and smooth out transient fluctuations in supply

6.11 Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage technology, similar to Pumped Storage Hydropower, is a mature technology which has been in use since the 1970s. Ambient air is captured and stored in compressed form in underground caverns or pressurized tanks by driving compressors using off peak excess energy . The air is compressed and stored and has a higher temperature due to the compression process. In a conventional diabatic CAES process, this heat is released into the atmosphere using coolers/radiators essentially wasting the heat energy which represents part of the electrical energy that was used for compressing the air. When energy demand increases, the air stored in the reservoirs or caverns are run through turbine generators. In this process of expansion of the air after being released from the storage unit, the air cools down and has to be heated to enhance the operation quality of the turbine/generator system. The re-heating of air requires additional fossil fuel or natural gas combustion which negates the policy of a complete clean and renewable energy system.

Recent developments in Advanced Adiabatic CAES (AA-CAES) technology uses thermal storage units where the heat that is usually wasted after compression is instead stored. This stored heat energy is used to re-heat air during the expansion process in the turbine/generator unit, when the system is called upon to provide for increased energy demand. This improves the efficiency of the system from about 60% to 70% as heat is not wasted but simply re-used.

Great investment and research is required to improve the efficiency through thermal storage units and recapturing waste heat from any nearby industrial sites. Only 2 large-scale CAES systems are operational as of today – Huntorf, Germany and McIntosh, USA and hence very little operational experience is available. A CAES system once built can have operational life for about 100 years and can have a 100,000 cycle life. The current estimated energy installation costs of these systems are $53 USD/kWh when the space used for the compressed air is a cavern underground and that is much cheaper than the battery technologies. The operation and maintenance costs can significantly increase if the air storage pressurised tanks are built specific for the system. When thermal storage systems are implemented, this increases operational complexity as they should be built to store heat at up to 600˚C.

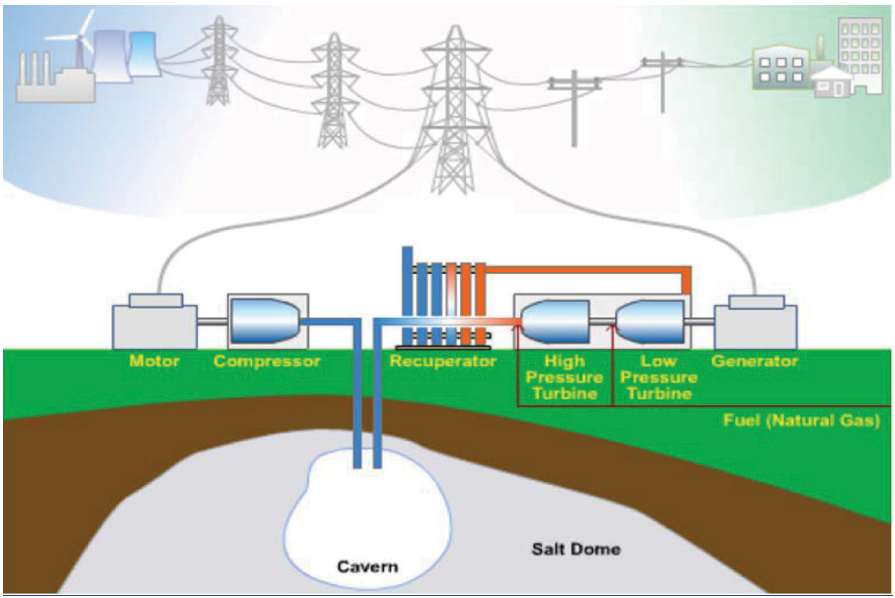

Figure 11: Schematic of CAES.
Source: DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA

CAES technology can be implemented for grid services like load balancing, peak shaving, increased RE grid integration. For large-scale storage, the volume of the air storage cavern or tank required will be greater. Finding a suitable naturally available salt cavern or unused mine or a depleted gas field for air storage can bring down the total investment cost, but these are highly dependent on suitable site availability and local environmental constraints. Building a system specific pressurised tank can greatly increase the cost and may not always be economical.

6.12 Synchronous condensers

Synchronous condensers do not exactly fit into the energy storage system category but they can be used to provide for grid services where other storage technologies are used. A Synchronous Condenser or Synchronous Capacitor has a shaft that spins freely and that is not connected to anything. Energy is stored in the form of kinetic energy in the spinning rotor of the machine and can be discharged when there is sudden voltage/frequency fluctuation in the electric grid. It is mainly used to improve the grid's power quality by either generating or absorbing reactive power to adjust the grid's voltage or improve the power factor.

Unlike other power plants like fossil fuel, natural gas or wind power plants, PV plants are not synchronous generators. PV power plants do not have any moving parts to provide grid inertia support. In such power plants, synchronous condensers can be useful to provide voltage and frequency regulation support. However, these are not a solution for a grid that completely relies on PV source, as PV modules do not generate energy after the sun is down and a synchronous condenser cannot operate like a battery.
Major product manufacturers like ABB, GE, and WEG offer complete synchronous condensers packaged solutions that are usually in the range of 10MVAR to 100MVAR. However, these are not quite suitable for renewable capacities installed less than this range and that is usually the case in the Pacific islands. Hence a synchronous condenser cannot be expected to be practical for improving grid stability due to increased solar or wind integration in most of the islands of the Pacific.

6.13 Comparison of Grid Storage technologies

The following table shows the comparison between major characteristic parameters of batteries discussed above.

Table 1: Comparison of Battery technologies

Technology	Energy Density (Wh/L)	Power Density (W/L)	Suitable Storage Duration	Discharge time	Lifetime (years)	Cycle Life (full-cycle)
Lead-acid	50-100	10-700	Minutes-Days	Second-Hours	5-15	250-2500
Lithium-ion	150-700	100-10,000	Minutes-Days	Minutes-Hours	5-20	1000-10,000
Capacitors	2-6	0-0.05	Seconds-Hours	Milliseconds-1 hour	1-10	>50,000
Nickel-based Batteries	20-300	80-600	Minutes-Days	Seconds-Hours	2-15	300-3,000
Flow Batteries	15-70	1-2	Minutes-Days	Seconds-Hours	5-20	12,000-14,000
Sodium-Ion	20-90		Minutes-Days	Minutes-Hours	>10	>5000
Sodium Sulphur	140-300	120-160	Minutes-Days	Minutes-Hours	10-25	1000-10,000
Pumped Hydro Storage	0-2	-	Hours-Months	1 to >24 hours	30-100	12,000-100,000
Flywheel	20-200	5,000-10,000	Seconds-Minutes	Seconds-15 minutes	15-25	100,000-1,000,000
CAES	2-6	0-1	Hours-Months	1 to >24 hours	20-100	10,000-100,000

7. Control and Monitoring with SCADA

7.1 Need for Optical Fibre Monitoring/Control between Different RE Power Systems, Storage Sites and Diesel Power Station(s)

Energy management is the process of monitoring, coordinating, and controlling the generation, transmission and distribution of electrical energy. The physical plant to be managed may include a variety of generating plants (diesel and renewable) and storage systems, each with their own unique capacity and response rate characteristics. They are producing energy that is fed through transformers to the high-voltage transmission network (grid) interconnecting the generation plants with the load centres. Step-down transformers in substations at the load centres transform the energy down to lower voltage sub-transmission and/or distribution levels for delivery to the end user via the local distribution network.

Since transmission and distribution grids do not themselves provide meaningful levels of energy storage, supply and demand must be balanced by either generation or load control. SCADA systems and other central control systems require reliable, secure, high-speed, moderate-bandwidth data links between the central control and each of the generation stations and distribution substations for the purposes of monitoring production, loads, protection relay status, switchgear conditions and other parameters. These data links also provide for central control of network plants, remote start/stop or variation of output of generators and remote open/close/reset of motorised switchgear such as circuit breakers or contactors at unattended substations are all common requirements. Sometimes this central control may even be extended to individual users in the case of large commercial and industrial loads.

Signals can also be relayed from the distribution substations (e.g. by frequency injection switching to trigger relays on/off) or directly from the central control via other means (wide area network, mesh network, wireless data etc.) to control groups of residential loads “behind the meter” (e.g. electric storage water heaters) / distributed generators (e.g. rooftop photovoltaic systems, domestic level energy storage systems with grid feed-in capabilities, etc.).

Fibre-optic data links, preferably buried to minimise the chance of damage, provide the necessary speed, bandwidth, reliability and security between the key grid infrastructure nodes such as the central control room, generation plant(s), storage plant(s) and distribution substations. Reliability is enhanced by provision of redundant links which follow physically separate routes. In addition, fibre-optics provide isolation protection against lightning strikes (which can damage equipment connected to copper Public Switched Telephone Network (PSTN) lines by inducing voltage spikes and surges), immunity to radio frequency interference (RFI) / electromagnetic interference (EMI) sources close to copper communications lines that may cause interference, and plenty of bandwidth for future expansion of data gathering.

7.2 Data Gathering from Solar Installations to Support Troubleshooting of Installations

Data gathering from PV installations via a SCADA system can take place from a multitude of sources:

- Plant level controller e.g. PLC (Programmable Logic Controller) that monitors a variety of plant data as well as controlling plant functions (e.g. tracking systems, automatic cleaning systems, inverter true power output levels, inverter reactive power output levels, switchgear).
- Where a PLC is in use a local PC (Personal Computer) is often used to run a SCADA client primarily dedicated to the local plant and designed for use by an onsite operator, With proper programming configuration and operator security authorisations, such a SCADA client could be used as a backup for the central control room in an emergency situation.
- Dedicated monitoring unit (e.g. RTU (Remote Terminal Unit) with little or no control capabilities, simply used for data aggregation and forwarding to the SCADA.
- Power / Energy meters – measure of overall installation performance at either or both the low voltage (LV) or MV/HV levels.
- Inverters – MPPT input(s), AC output and status information.
- String level monitoring equipment – Individual string voltages, currents etc.
- Local weather – irradiation at the array tilt and orientation, ambient air temperature, cell temperature and wind speed sensors can feed back data into the local SCADA where a software "reference model" of the plant can be used to calculate the expected system output in real time and compare it to real measured values to identify possible faults.

To make data acquisition by the SCADA system as simple as possible and to allow retrofitting of data acquisition equipment in the future the following points should be considered when specifying equipment:

- Provision of industry standard communications wiring connections on all equipment, including inverters (e.g. RS485 or 100Mbit Ethernet) rather than proprietary, hardware manufacturer systems.
- Use of industry standard communications protocols (e.g. MODBUS RTU, MODBUS TCP-IP, etc.) rather than proprietary, hardware manufacturer specific protocols.
- If industry standard communications outputs are not available then for integration purposes, industry standard voltage free relay contacts and/or analog inputs/outputs (e.g. 0-10Vdc or 4-20mA) should be specified for compatibility with standard PLC input/output capabilities rather than being tied to a specific manufacturer.
- Minimise communications overhead for the SCADA system by providing a local data aggregation system (this could be a local SCADA client) so that bulk data reads can be carried out by the main SCADA system rather than having to poll each device individually.

7.3 Data Gathering from Weather Monitoring Stations to Support Cloud Cover Monitoring and Near-Term PV system Output Forecasting

Data gathering from network weather monitoring stations via a SCADA system can be used to monitor cloud cover / movement and predict when changes in PV system output due to weather changes can be expected. The size of the monitoring network and distance from each monitoring station to the PV system as well as the speed that weather conditions are changing will affect the accuracy and lead time of such forecasting.

To make data acquisition by the SCADA system as simple as possible and to allow retrofitting / modification of data acquisition equipment in the future the following points should be considered when specifying equipment:

- Provision of industry standard communications wiring connections on all equipment (e.g. RS485 or 100Mbit Ethernet) rather than proprietary, hardware manufacturer systems.

- Use of industry standard communications protocols (e.g. MODBUS RTU, MODBUS TCP-IP, etc.) rather than proprietary, hardware manufacturer specific protocols.
- If industry standard communications outputs are not available, then industry standard voltage free relay contacts and/or analog inputs/outputs (e.g. 0-10Vdc or 4-20mA) should be specified for compatibility with standard PLC input/output capabilities rather than being tied to a specific manufacturer for integration purposes.
- Minimise communications overhead for the SCADA system by providing a local data aggregation system (this could be a local SCADA client) so that bulk data reads can be carried out by the main SCADA system rather than having to poll each device individually.

8. Case Studies

8.1 Tonga

Mata'a e La'a Solar Facility in Vaini has 1MW of PV capacity installed with 1MW of Lithium-ion capacitor banks that was commissioned in March 2015. 0.5MW of the battery capacity is installed in this site and another 0.5MW of Lithium-ion capacitor bank is installed at Maama Mai Solar Facility in Popua power station each with 11kWh capacity. The Maama Mai Solar Facility consists of 1.4MW of PV which was commissioned in July 2012 and was funded with NZD 7.9million by the NZ Aid Programme. The Mata'a e La'a Solar Facility incorporates a microgrid control system to work in tandem with the Maama Mai Solar Facility and other future renewable projects in Tonga. The total project with 1MW of PV capacity and 1MW of Lithium ion capacitor battery banks was implemented at a cost of $15million USD by the Government of Japan. The Mata'a e La'a Solar Facility and Maama Mai Solar Facility together results in an approximate annual saving of 831,465 litres of diesel.

8.2 Samoa

Apolima Island in Samoa has a 100% renewable energy supply. In 2005/2006, a mini-grid comprising of a 13.5kW PV system with a lead-acid battery storage system was installed. The system was over-sized to meet the expected energy demand of 100 residents living on the island, although they agreed not to use high-power electric devices like electric kettles and electric cookers during cloudy periods and also to only purchase energy efficient equipment. The system incorporates stacked inverters rather than a single central inverter for scalability purposes in the future. The system was installed at a cost of $223,500 with support from the Organisation for Sustainable Energy and United Nations Developement Programme.

8.3 American Samoa

Tesla has installed a battery system in the island of Ta'u. This system includes 60 Tesla Power packs capable of storing a total of 6MWh of energy and supplying 1MW of peak power. The battery has been designed with 3 days of autonomy for the design load. It is connected to a 7-acre, 1.4MW PV array that provides excess generated energy to charge the batteries. The installation provides for almost 100% of the energy demand in the island saving the island about 500,000 litres of diesel consumption per year. On Ta'u, the cost of diesel generated electricity was 65c/kWh before the PV and battery system was installed. After the microgrid installation, electricity is supplied at a cost of only 32c/kWh. The total project cost of $11million USD.

8.4 Tuvalu

In April 2018 a tender was released for the installation of a new 700kW$_p$ solar system and a 1MW/1MWh Energy Storage System (ESS). The objective is that when combined with the existing solar systems the solar energy storage system should be capable of supplying power for up to 6 hours on sunny days without the need for a fuel generator.

During the day the ESS will operate in grid-forming mode for use with intermittent RE generators and diesel generator management. In this mode, the ESS will be required to:

- absorb excess RE generation when required
- curtail PV generation if required
- inject power as required to support variation in PV generation,
- call on diesel generators when battery state of charge is not sufficient to continue in diesel-off mode
- ramp generators as required to meet loads
- control voltage and frequency on the network
- meet power quality requirements as described in PSR.

At other times the ESS will be in grid-following mode, with diesel generators forming the grid. In this mode, the ESS will be required to:

- Smooth output of intermittent RE generation
- Provide reactive power support
- Absorb or inject power to prevent under/over-loading of generators
- Meet power quality requirements as described PSR.