PowerWater

SOLAR/DIESEL MINI-GRID HANDBOOK

2ND EDITION

ARENA

Australian Government
Australian Renewable Energy Agency

This project is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA). ARENA was established by the Australian Government on 1 July 2012 to improve the competitiveness of renewable energy technologies and increase the supply of renewable energy in Australia. The agency's expertise, deep understanding of the renewable energy sector and willingness to fund innovative and ground-breaking projects means it provides a pathway to commercialisation for many new technologies and businesses. ARENA also shares knowledge, insights and data from funded projects to help the renewable energy industry and other projects learn from each other's experiences. More information is available at www.arena.gov.au.

PowerWater

Power and Water Corporation, through its not-for-profit subsidiary Indigenous Essential Services Pty Ltd (IES), is responsible for the provision of energy, water and wastewater services to 72 nominated remote Aboriginal communities and 79 outstations across the Northern Territory. Power and Water is also the generator for five minor centres across the Northern Territory. To service these communities, Power and Water operates more than 50 isolated mini-grid power systems, most of which rely on diesel fuel for power generation.

Electricity demand in remote Northern Territory communities is forecast to increase, as a result of government infrastructure development, service improvement and housing programs, and population growth. At the same time the price of diesel fuel is volatile, affected by global supply constraints and exchange rate movements. An ongoing reliance on diesel fuel for remote power generation represents considerable and increasing financial risk.

Cover ‣ *SETuP solar array at Kaltukatjara (Docker River).*

‣ *Civil works at the Daly River solar array.*

Power and Water is committed to delivering least cost, reliable and safe electricity services to remote Aboriginal communities and has long pursued alternative energy source options. Power and Water recognises the opportunity solar technologies present to reduce the reliance on diesel fuel and drive down operational expenditure.

Power and Water has a track record of close to three decades of owning and operating solar/diesel hybrid systems in remote Aboriginal communities. Through the Solar Energy Transformation Program (SETuP) and other recent projects, Power and Water achieved a step-change in its remote generation portfolio, with the hybridisation of a majority of the diesel mini-grid fleet to include solar. This includes an installed capacity of over 11 MW of flat plate solar, as well as an 800kVA Battery Energy Storage System (BESS) at Daly River, with solar contributing 10% to remote community energy needs at the time of publication.

Power and Water is committed to industry knowledge sharing in order to strengthen the collective experience and expertise in hybrid mini-grid system planning, implementation and operation. This approach is intended to foster the ongoing development of high quality integrated, efficient solar/diesel hybrid power systems across Australia.

Disclaimer

1 ACRONYMS

ARENA	Australian Renewable Energy Agency
AVR	Alternator voltage regulator
BESS	Battery energy storage system
BOM	Bureau of Meteorology
CPT	Cloud Prediction Technology
CPV	Concentrating Solar Photovoltaics
CSO	Community Service Obligation
ESS	Energy Storage System
GHz	Gigahertz
GSS	TKLN Solar Project Grid Stability System
Hz	Hertz
IEA PVPS	International Energy Agency Photovoltaic Power Systems Program
IES	Indigenous Essential Services Pty Ltd
ICEG	Indigenous Community Engineering Guidelines
kW	Kilowatt
kWh	Kilowatt hour
LAN	Local area network
LCOE	Levelised Cost of Energy
MJ/m2	Megajoules per metre-squared
MW	Megawatt
MWh	Megawatt hour
MWp	Megawatt peak
NPC	Net present cost
NPV	Net present value
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
PPA	Power Purchase Agreement
PV	Photovoltaic
REF	Renewable Energy Fraction
RPF	Renewable Power Fraction
RPM	Revolutions per minute
SCADA	Supervisory control and data acquisition
TKLN	Ti Tree, Kalkarindji, Lake Nash (TKLN Solar Project)

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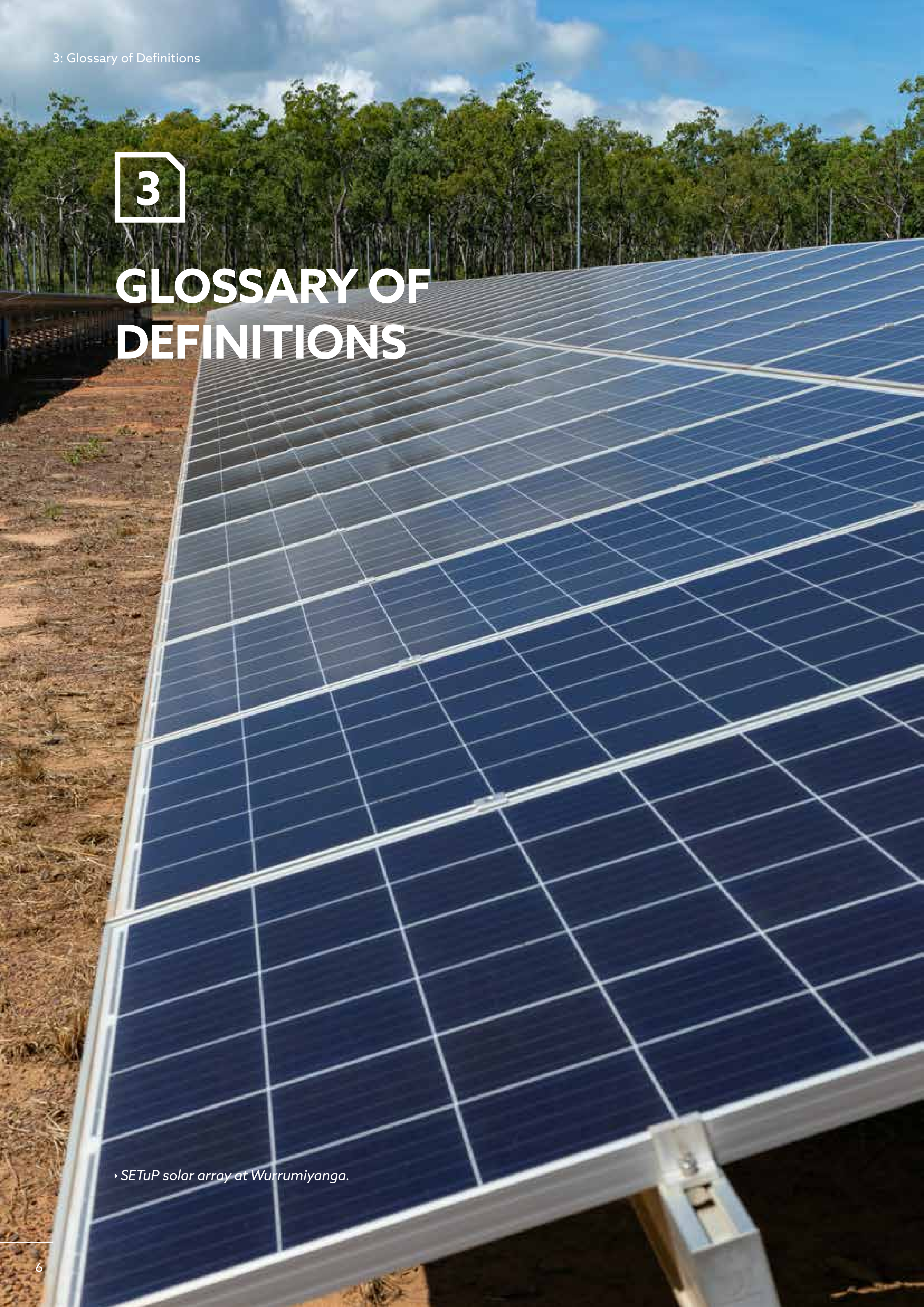

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GLOSSARY OF DEFINITIONS

‣ *SETuP solar array at Wurrumiyanga.*

Inside the Daly River power station.

Agreed Service Levels

Power and Water has responsibility for the provision of reliable essential services (power, water and wastewater treatment) to 72 remote Aboriginal communities across the Northern Territory. The minimum service levels to be provided by Power and Water are based on the Northern Territory Government's Indigenous Community Engineering Guidelines. Power and Water reports to the Northern Territory Government on performance against these minimum service levels however they are not regulated by the Northern Territory Utilities Commission or the Australian Energy Regulator.

Community Service Obligation (CSO)

In the handbook, the term CSO refers to the payment the Northern Territory Government provides to Power and Water in order to fund the shortfall between the cost to supply electricity in remote Aboriginal communities and the revenue recovered from customers at the tariffs set by Government.

Energy storage

Refers to a way of keeping a reserve of energy that can be used at a later stage. Typically energy storage is classified as either 'long-term' or 'short-term'. Long-term energy storage is used to provide energy over long periods, such as overnight in small solar/battery systems. Short-term energy storage is used to provide power over short periods, such as smoothing the intermittent output of a solar system in a solar/diesel mini-grid. There are various energy storage technology types suited to different applications including batteries, pumped hydro, compressed air, super-capacitors and fly wheels. The dominant energy storage technology at present for mini-grid systems is lithium-ion batteries.

Levelised Cost of Energy (LCOE)

A constant unit cost ($/kWh or $/MWh) of electricity supplied that has the same present value as the total cost of building and operating the system over its life (typically 20 years). LCOE for hybrid solar/diesel systems incorporates all ongoing system costs (for both solar and diesel infrastructure), however typically only includes the capital costs of the solar component. This is because the existing diesel infrastructure represents a 'sunk cost'. There are multiple ways to calculate LCOE, depending on the level of financial detail. LCOE is useful in comparing technologies with different operating characteristics, however results are highly sensitive to input assumptions so they must be kept consistent across technologies to enable a reasonable comparison.

Load management

Refers to the context where the load is managed in order to optimise generator or network performance. In the handbook, load management specifically relates to the direct controlling and interrupting of loads in order to optimise power system operation, for example to manage power station stability during times of intermittent solar output.

Power and Water employees Sam Parisi and Jeff Adams at the switchboard at the Wurrumiyanga solar compound.

Minimum loading

Refers to the minimum recommended load factor (%) of a diesel engine. Diesel engines can be damaged by extended operation below the minimum load factor which may reduce engine performance and cause premature engine maintenance or rebuilding. The minimum loading of diesel engines is a manufacturer-recommended specification and can be in the order of 40% of name plate rating. Typically if the loading on an engine reaches the minimum load factor, the control system will call online a smaller generator, which is better suited to the load demand. Manufacturers are now offering models that can be loaded at 10% or lower for extended periods so long as periodic higher loading requirements are met, providing significantly more flexibility and PV hosting capacity.

Minimum runtime

Refers to the minimum length of time a generator must be online before the control system can take it offline. This setting ensures that small fluctuations in load do not cause excessive cycling of generators, which induces unnecessary wear and tear on the engines.

Mini-grid

Refers to an isolated power system which operates autonomously, i.e. manages and controls line voltage and frequency, real and reactive power flow and balances power supply with power consumption.

Renewable Fraction, Contribution or Penetration

The contribution from solar in hybrid mini-grid systems is classified in this document by two numbers, renewable energy fraction and renewable power fraction. Energy fraction (average contribution, [kWh/kWh]) is the fraction of total energy solar provides to the system over a specified period, usually assessed on a per annum basis. Power fraction (instantaneous contribution, [kW/kW]) is the fraction of power solar provides instantaneously to the power system. For example, a solar system may reach 80% instantaneous power fraction at times and achieve a 30% annual energy fraction overall. The words 'contribution' or 'penetration' may also be used to refer to the relative input from renewables.

Power Purchase Agreement (PPA)

Refers to a contract between two separate entities regarding the supply and purchase of electricity. Power and Water utilises PPA contracts with independent third parties for the supply of electricity to six remote Aboriginal communities. Under these PPA models, Power and Water procures only kWh units from the third party. This means, crucially, that Power and Water is responsible for providing, maintaining and operating the distribution infrastructure in the community (i.e. the grid network) and providing retail services (including managing the connection and disconnection of services, metering and billing, supporting the connection of small-scale customer-owned solar photovoltaic (PV) systems, informing and educating customers about water and energy efficiency, etc). Under the PPA models that relate only to the supply of solar energy (i.e. the TKLN Solar Project), Power and Water is responsible for the provision of reliable power overall. This means that Power and Water continues to operate and maintain the diesel power station and all related power distribution infrastructure, as well as providing the aforementioned auxiliary services (retail, metering and billing, etc). Under this model, Power and Water also ensure that sufficient diesel generation capacity exists to supply reliable power in the event that the solar power station is offline.

Power station

Refers to the primary site of power generation and power system control in remote communities serviced by Power and Water. Power and Water operates more than 50 mini-grid power stations, the majority of which rely on diesel fuel as the primary source of power generation. These power stations vary in size from 300kW up to 5MW, with local diesel storage sufficient for at least six weeks of operation. They typically incorporate a local automated control and protection system, with a secure link to Power and Water's central supervisory control and data acquisition (SCADA) network.

Quality of supply

Refers to the delivery of electricity in line with the Agreed Service Levels, for example control of frequency and voltage within agreed envelopes, and staying within targets for outage duration and frequency.

Remote Aboriginal communities

Refers to the 72 nominated remote communities that are on Aboriginal owned land that Power and Water (via its not-for-profit subsidiary IES) is responsible for providing essential services (power, water, wastewater) to, on behalf of the Northern Territory Government. For a map of these locations, refer to Appendix 9.1.

Smoothing

Refers to the act of reducing the acuteness of solar output fluctuations during intermittent cloud events. This function is commonly provided by energy storage systems.

Solar

In the handbook the term 'solar' refers to flat-plate solar PV technology, not solar thermal or concentrating PV technology.

Solar/diesel mini-grid

In the handbook the term solar/diesel mini-grid describes a hybrid isolated mini-grid power system using solar, diesel and potentially BESS generation operating in a remote community serviced by Power and Water in the Northern Territory. The characteristics of these mini-grids that set them apart from other solar/diesel hybrid mini-grid systems operating in other jurisdictions and internationally include the pre-existence of a diesel power station and associated legacy infrastructure, demand-driven supply expectations, centralised generation and a uniform tariff. Attempts have been made to highlight where similarities exist between solar/diesel mini-grids in the Northern Territory and those that exist elsewhere.

Spinning reserve

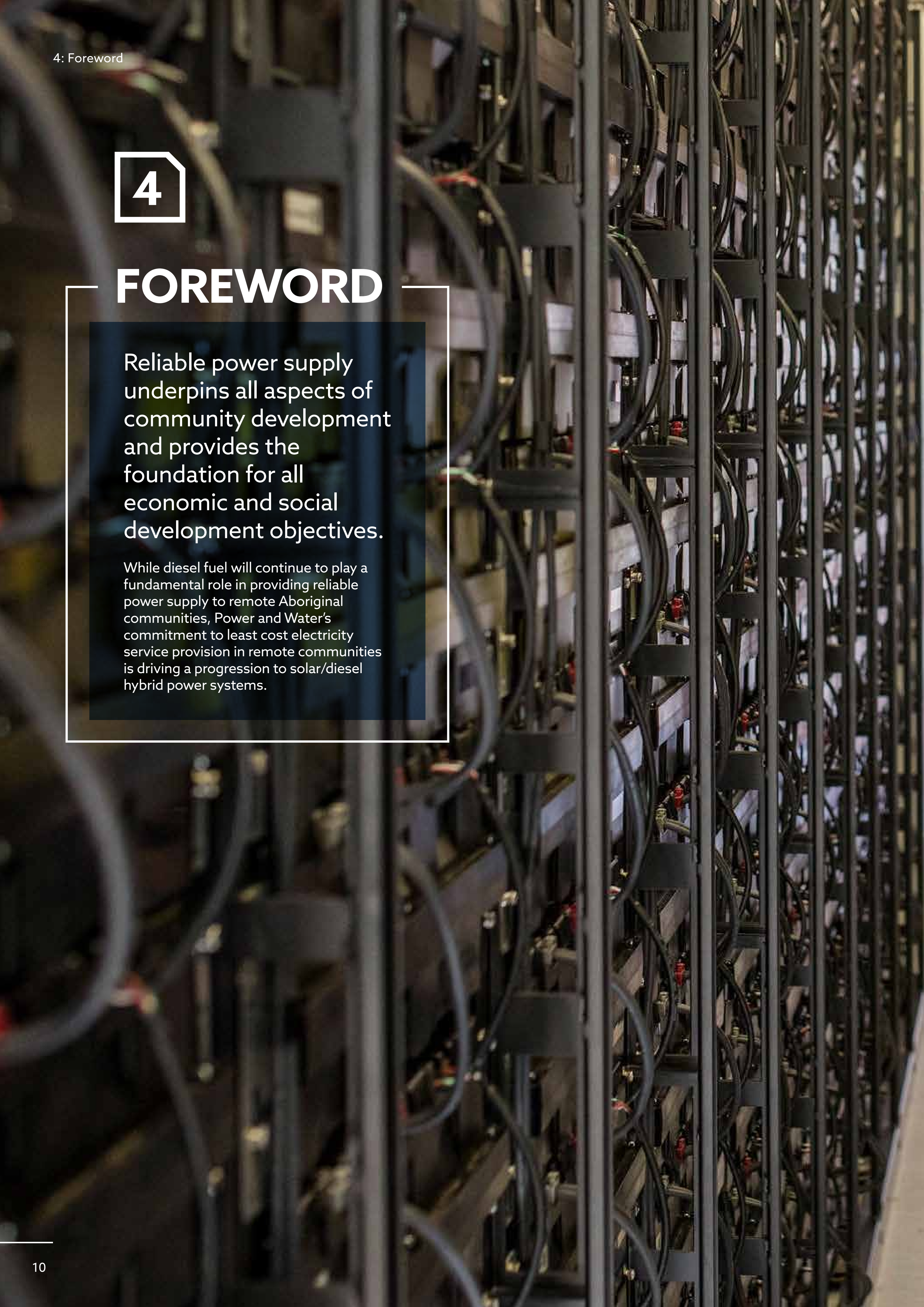
Refers to the amount of spare diesel generator capacity that is online and available to instantaneously service additional load. Spinning reserve is carried in order to manage normal community load fluctuations. In the case of solar/diesel hybrid systems, additional spinning reserve may be required in order to service any unmet load in the event of a reduction in solar output (such as during a cloud event).

Net Present Cost (NPC) or Net Present Value (NPV)

Is the sum of discounted cash costs and incomes over the life of the asset. It is the preferred metric for selection of power system designs to ensure systems are least cost over the whole of the asset life.

Uniform tariff

The Northern Territory Government operates a uniform tariff policy, which means that all (non-contestable) customers in the Northern Territory pay the same price for electricity ($/kWh). Due to the high cost of remote power generation, the revenue recovered from customers in remote communities via the uniform tariff does not represent full cost-recovery. The Northern Territory Government subsidises electricity for remote community customers via the Community Service Obligation (CSO).



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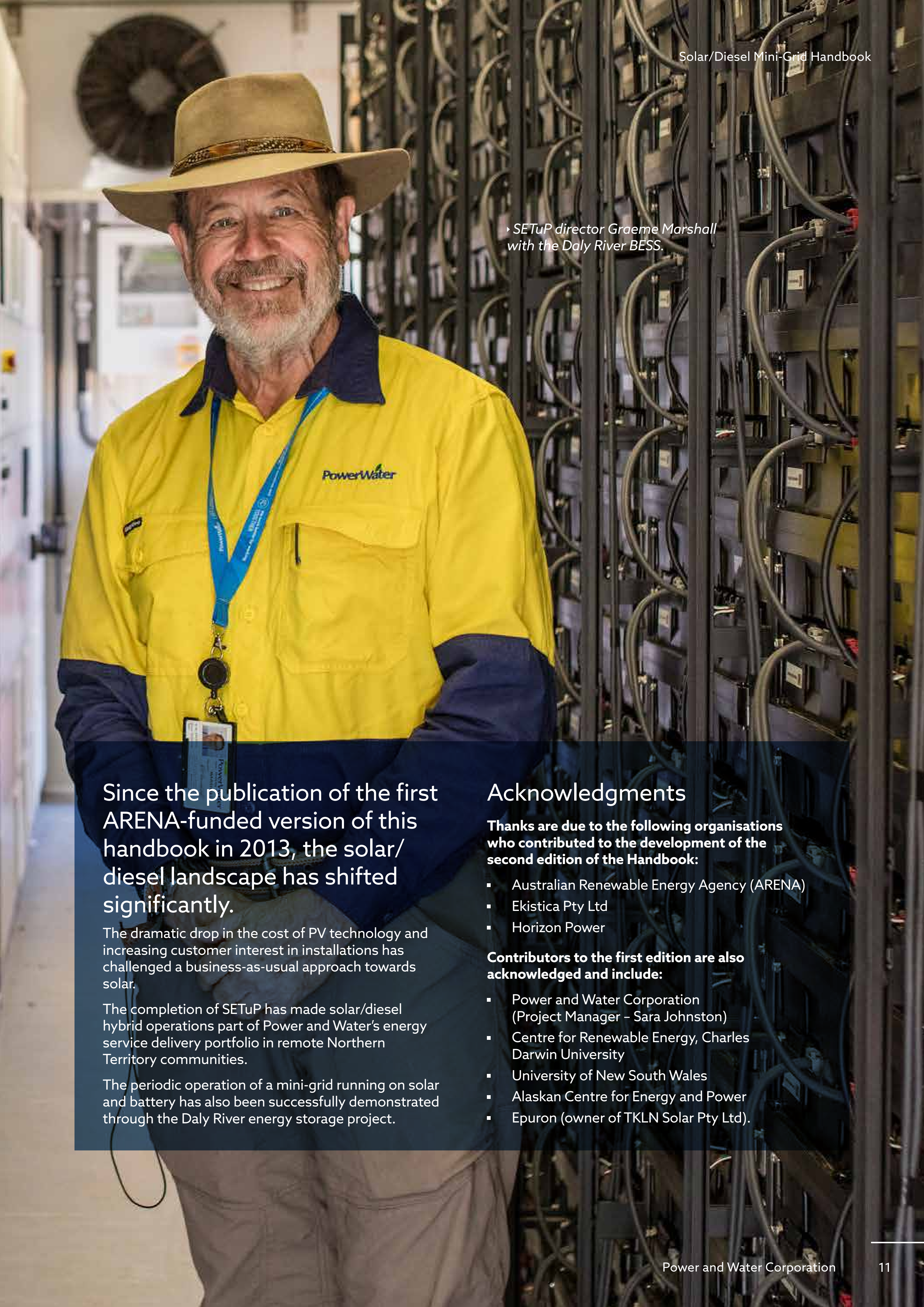
FOREWORD

Reliable power supply underpins all aspects of community development and provides the foundation for all economic and social development objectives.

While diesel fuel will continue to play a fundamental role in providing reliable power supply to remote Aboriginal communities, Power and Water's commitment to least cost electricity service provision in remote communities is driving a progression to solar/diesel hybrid power systems.



SETuP director Graeme Marshall with the Daly River BESS.

Since the publication of the first ARENA-funded version of this handbook in 2013, the solar/diesel landscape has shifted significantly.

The dramatic drop in the cost of PV technology and increasing customer interest in installations has challenged a business-as-usual approach towards solar.

The completion of SETuP has made solar/diesel hybrid operations part of Power and Water's energy service delivery portfolio in remote Northern Territory communities.

The periodic operation of a mini-grid running on solar and battery has also been successfully demonstrated through the Daly River energy storage project.

Acknowledgments

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- Australian Renewable Energy Agency (ARENA)
- Ekistica Pty Ltd
- Horizon Power

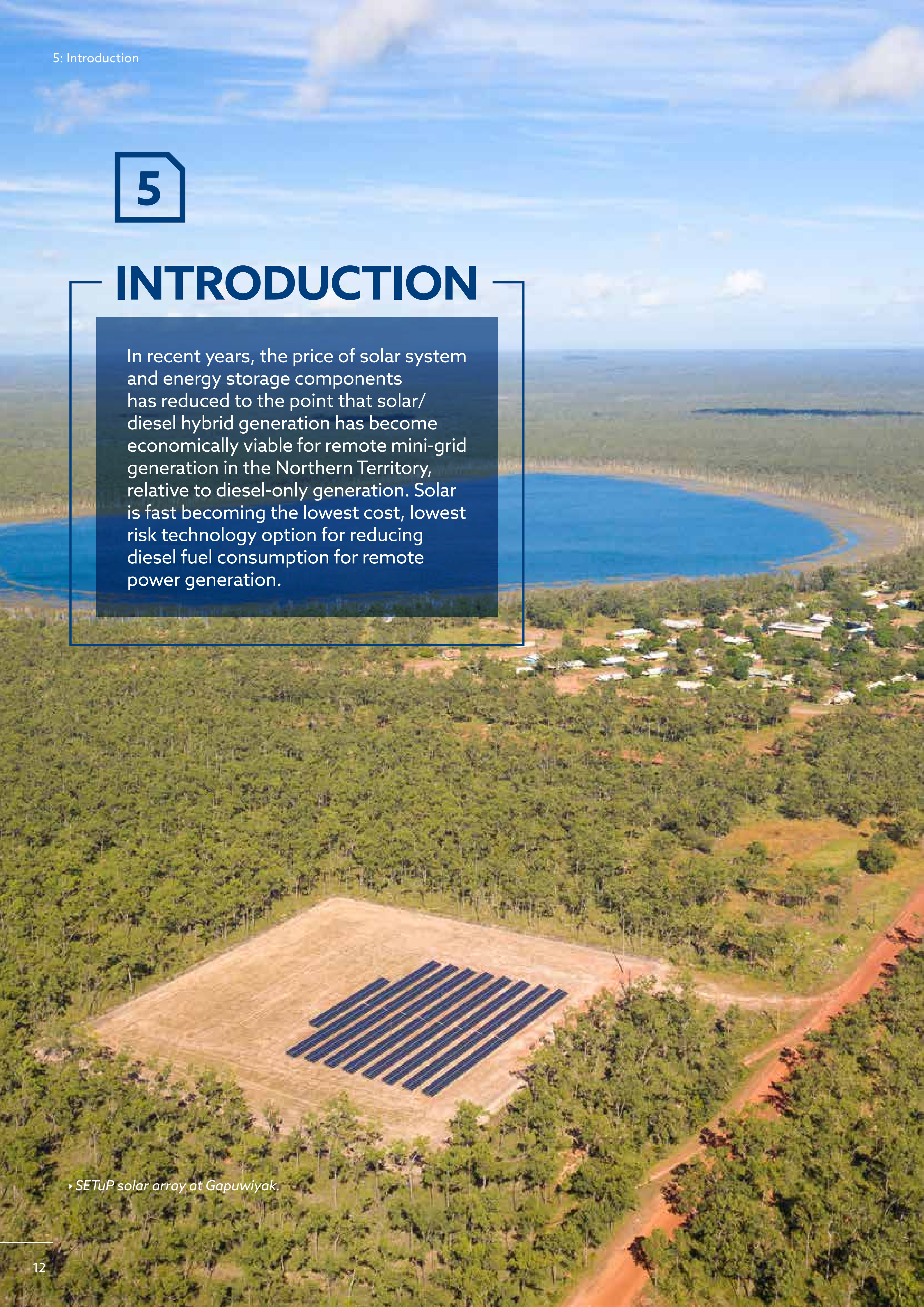
Contributors to the first edition are also acknowledged and include:

- Power and Water Corporation (Project Manager – Sara Johnston)
- Centre for Renewable Energy, Charles Darwin University
- University of New South Wales
- Alaskan Centre for Energy and Power
- Epuron (owner of TKLN Solar Pty Ltd).

5

INTRODUCTION

In recent years, the price of solar system and energy storage components has reduced to the point that solar/diesel hybrid generation has become economically viable for remote mini-grid generation in the Northern Territory, relative to diesel-only generation. Solar is fast becoming the lowest cost, lowest risk technology option for reducing diesel fuel consumption for remote power generation.



SETuP solar array at Gapuwiyak.

The overarching objective of the handbook is to provide information about the key technical, design, implementation and operational considerations when planning solar/diesel hybrid mini-grid systems in remote Australia.

Minister for Essential Services Gerry McCarthy, Nauiyu community elder Mark Casey and Power and Water Chief Executive Michael Thomson at the Daly River BESS.

The handbook is intended to be a useful reference tool for the Australian off-grid solar/diesel industry, to aid solar/diesel hybrid system decision making and assist renewable energy technology suppliers develop and provide solutions for remote power generation. The handbook provides a contextual overview to new entrants in the solar/diesel mini-grid space, including on-grid solar developers keen to tap into the off-grid market and the general public interested in the challenges and opportunities associated with 'hybridising' existing diesel mini-grids.

There are a myriad of types and designs of mini-grid systems operating around the world which have distinct attributes and constraints. Therefore, it is important to emphasise that the handbook is focused primarily on mini-grids owned and operated by Power and Water in the Northern Territory, servicing remote Aboriginal communities on behalf of the Northern Territory Government. Throughout the handbook, where content is relevant also for mini-grids operating in other jurisdictions in Australia and/or internationally, attempts have been made to note this in text boxes adjacent to the main text. In addition, key sources of information addressing other areas of the solar/diesel hybrid mini-grid spectrum not covered in the handbook, such as reports published by the International Energy Agency Photovoltaic Power Systems (IEA PVPS), which may be of interest to readers have been highlighted.

Throughout the handbook, case studies of existing hybrid systems have been cited to demonstrate application of the considerations and issues discussed. The primary case studies referred to are from the Solar Energy Transformation Program (SETuP).

- SETuP medium contribution rollout of diesel solar hybrids with 9MW of solar for 24 communities, targeting 15% annual diesel savings without requiring supporting technologies
- SETuP Daly River project combining a 1MW PV array with a 2MWh BESS to enable high solar contribution diesel off operation and 50% annual diesel savings.

SETuP solar array at the Areyonga power station.

5.1 Mini-Grid Definition

The International Energy Agency defines a mini-grid as 'a set of electricity generators and, possibly, energy storage systems interconnected to a distribution network that supplies the entire electricity demand of a localised group of customers'.

The term mini-grid is applied to power systems of various sizes and levels of complexity however with increasing system size the operating characteristics and constraints of mini-grids change. In order to distinguish between mini-grids of different scale three broad classifications of mini-grids are recognised internationally:

1. Village micro-grids (e.g. rural electrification in developing countries, supplying limited power for basic needs)
2. Diesel mini-grids (e.g. isolated grids servicing remote communities across Australia
3. Urban/industrial mini-grids (e.g. isolated grids servicing remote mining operations; or sections of large urban grids which can disconnect from the urban grid and operate autonomously which are commonly referred to as micro-grids).

The handbook is focused on (2), specifically diesel mini-grids servicing remote Aboriginal communities in the Northern Territory with generation capacity between 300 kilowatts (kW) – 5 megawatts (MW). The concepts apply also to gas mini-grids, however the lower fuel cost of gas generation means that diesel grids remain a priority for hybrid operation.

Further information

IEA PVPS Task 11 – PV Hybrids and Mini-Grids produced a number of reports on the characteristics of hybrid mini-grids relative to small-scale solar home systems and large urban electricity networks. These can be found at www.iea-pvps.org. IEA PVPS Task 11 is also a good source of information regarding the strengths and weaknesses of solar/diesel mini-grid system architecture options, including centralised or decentralised generation, AC, DC or AC and DC coupling as well as and mini-grid control methods. IEA PVPS is a good starting point for a literature review of international work in solar/diesel mini-grid systems.

5.2 Northern Territory Context

In the Northern Territory, Power and Water through its not-for-profit subsidiary Indigenous Essential Services Pty Ltd (IES) is responsible for the provision of reliable utility-grade electricity services to 72 nominated remote Indigenous communities and 79 outstations across the Northern Territory. Power and Water also operates mini-grids in several minor centre remote communities outside of the IES agreement (not on Aboriginal land).

To achieve this, Power and Water operates and maintains over 50 diesel mini-grid power stations between 300kW and 5MW capacity with a total installed diesel capacity of over 74MW and over 1 000km of power distribution lines. With the completion of recent projects including the SETuP program, the infrastructure now includes 1.8MW DC of utility flat plate PV arrays and an 800kVA BESS across 30 communities.

The key characteristics of Power and Water mini-grids are outlined below.

- Diesel is still the primary source of power generation – this is the case even in the operating solar/diesel hybrid systems. This is a key distinction from micro-grids and mini-grids whose primary source of power is renewable energy (e.g. solar), with the diesel generators used solely as back-up or standby supply. This distinction has operation and design implications.
- Generation is centralised – a single power station services the mini-grid. In the case of hybrid solar/diesel systems, the solar power station is situated adjacent to the diesel power station wherever possible. While the level of distributed generation is increasing in remote communities (i.e. customer-owned rooftop solar), these systems are relatively small in comparison to the scale of the centralised diesel power station. There is no communications link between these systems and the power station; they are not controlled and essentially act as negative load. The uptake of customer PV is limited by power system constraints imposed by Power and Water, but also by socio-economic factors in the community.
- Fully-automated control and SCADA – remote power systems are managed on a continuous automated basis. The solar-diesel system interface occurs either in the power station with the solar feeder connected to the main switchboard, or via a direct connection of the solar array to a high voltage feeder.
- Power and Water-owned – almost all mini-grid infrastructure and assets in major remote Aboriginal communities are owned by Power and Water subsidiary IES, including power stations, electricity distribution networks and fuel storage; the exception being some solar power stations which are operated under a PPA with a third party. Power and Water is responsible for providing generation, distribution and retail functions to remote community customers.
- Quality of supply – Power and Water is contracted to provide reliable, safe, utility-grade power and meet service outcomes as outlined in the ICEG.
- Mini-grid design and operation is demand-driven – customer supply expectations are high and Power and Water must design and operate the power system in order to satisfy customer demand. This is distinct from economically constrained mini- and micro-grids where demand must stay within the capacity of existing assets (typically solar and batteries with diesel backup).
- Power and Water is licensed by the Northern Territory Utilities Commission to generate and retail electricity to customers in remote Aboriginal communities and regulated retail electricity prices are set by the Northern Territory Government. The Northern Territory Government has a uniform tariff policy, meaning that all non-contestable electricity customers pay the same electricity tariff. The electricity tariff is lower than the cost to provide reliable electricity supply in remote Aboriginal communities.
- The cost to supply electricity services is much higher than revenue recovered through tariffs. The Northern Territory Government provides a subsidy to Power and Water in the form of a community service obligation (CSO) payment to fund the shortfall.
- The performance of the diesel mini-grid is not regulated by the Utilities Commission, however Power and Water is required to satisfy minimum service levels (acceptable voltage, frequency and interruption limits) including those in the ICEG.
- Power and Water mini-grids are isolated systems. They are not interconnected into larger networks. Power and Water has interconnected some remote Aboriginal communities into small regional mini-grid networks supplied by a single power station, where it has been economically efficient to do so.

For more information regarding the operation of Power and Water's remote mini-grid power systems, refer to section 6.2 of this handbook. A map of the 72 remote Aboriginal communities serviced by Power and Water is included in Appendix 9.1.

Case study: Solar Energy Transformation Program (SETuP) overview

Power and Water Corporation has integrated solar into its diesel mini-grids in remote and regional communities for more than 20 years. With a diesel spend of up to $30 million annually, Power and Water's operational costs are exposed to high price volatility and high costs of transport and storage of diesel fuel.

Following the 2012 Nauiyu feasibility study and publication of the first edition of this handbook, Power and Water designed a program to apply the principles within the handbook to integrate solar into the majority of its isolated diesel power stations. With a successful funding application to the Australian Renewable Energy Agency (ARENA) and support from the Northern Territory Government, the Solar Energy Transformation Program (SETuP) was established.

The focus for the $59 million program was on diesel-powered communities who received services through Power and Water's subsidiary, Indigenous Essential Services (IES). The design incorporated two main components which together would make solar an established part of operation, and simultaneously demonstrate the technologies required to support higher levels of solar contribution.

The first component of SETuP was the integration of utility solar arrays at 24 remote communities, working alongside the existing diesel engines at a 'medium contribution' level to achieve 15% average diesel savings without requiring additional supporting technologies. By deploying established solar technologies in a low-risk way and at scale, solar hybrid would become part of everyday operations.

The second component was pilot deployments of technologies to enable higher levels of solar integration. This included the flagship project at Nauiyu (Daly River) combining a 1MW solar array with a 2MWh battery energy storage system (BESS), allowing for 100% of solar energy use during the day with diesel engines operating at night. Trials of integrating cloud forecasting and direct load control were also incorporated into the program design.

The program successfully achieved its goal of deploying 10MW of operating solar capacity in early 2019. Across the 25 participating communities, 94 million litres of diesel are anticipated to be saved over the 20-year design life.

An important additional goal for the SETuP project partners was to share the learnings and knowledge gained from the project in order to support the broader adoption of solar integration into remote diesel grids.

A full list of SETuP communities is provided in 9.2, and further details on the medium contribution and Daly River projects are included in case studies in section 7.

Solar array in Gunbalanya.

Case study: Ti Tree, Kalkarindji, Lake Nash (TKLN Solar Project)

The TKLN Solar project was an important precursor to and impetus for the SETuP program. Completed in 2013, it involved the integration of high contribution solar systems to the existing diesel power stations at three remote Northern Territory communities, Ti Tree, Kalkarindji and Lake Nash (Alpurrurulam). The populations of these communities are approximately 170, 390, and 490 respectively.

The primary project driver was to minimise diesel fuel consumption at the three communities and reduce the long term electricity generation costs. It received funding from the Northern Territory Government, and the Australian Government through the former Renewable Remote Power Generation Program (RRPGP).

Significant load growth had recently been observed and two of the three communities had at that time suffered restrictions in fuel deliveries due to inclement weather. It was recognised that displacing diesel consumption with solar would improve supply security by providing a hedge against future weather events and diesel price volatility.

The total renewable energy capacity installed across the TKLN communities exceeded 1MWp, consisting of 992kW of solar (Kalkarindji 402kW, Ti Tree 324kW, Alpurrurulam 266kW) and 45kW of wind turbines at Alpurrurulam.

TKLN Solar Project – map

The systems were designed for solar to produce up to 85% of power demand at a given instant, meeting up to 30% of the average daily energy requirements for those communities. This was a significant scale at the time. It achieved ramp rate control of solar output using battery storage to allow for higher solar contribution levels alongside traditional diesel engines whose operation required quite high minimum loading levels.

The investment was based on a PPA contract model, with Power and Water entering into an agreement to purchase an amount of energy per annum (MWh) with the owner of the solar power stations, TKLN Solar Pty Ltd (a wholly-owned subsidiary of Epuron Pty Ltd).

Ti Tree solar array

6 DIESEL MINI-GRIDS

Diesel engines have a long history of supplying remote power generation in Australia. This chapter presents the key characteristics of diesel engine technology that have led to its ubiquitous use in this challenging operating context. It also outlines some of the advantages and disadvantages associated with using diesel fuel for remote power generation.

Diesel storage in Ramingining.

6.1 Diesel Engines

Diesel engines are the most common electricity generation method used in remote mini-grids.

Listed below are the key characteristics and advantages of diesel engines for remote power generation relative to other generation options.

- Low capital costs – due to their widespread application and manufacturing.
- High reliability – diesel engines are robust, proven, sturdy machines, well suited to harsh operating environments such as the Northern Territory climate. Engine maintenance is based on run hours and is therefore fairly predictable.
- Quick start and loading – diesel engines can be brought online quickly if required and require minimal warm-up time before being able to accept load in comparison to other fossil fuel generation.
- Good load following capabilities – diesel engines are responsive to load fluctuations.
- Good part load efficiencies – diesel engines are able to service loads below their ideal loading (~80%) with reasonable efficiency (i.e. efficiency curve is not linear).
- Servicing skills are common – diesel engine operation and maintenance (O&M) does not require highly specialised skills due to the prevalence and long history of diesel engine operation.
- High energy density of fuel – a low energy density would mean that higher volumes of fuel would be required to generate the same amount of electricity, increasing the fuel delivery and fuel storage requirements.
- Storage capacity – diesel fuel is able to be stored for extended periods at relatively low cost, particularly important for remote isolated regions with intermittent transport access
- Quick installation – diesel engines are relatively easy to install.

Diesel generator at Wurrumiyanga power station.

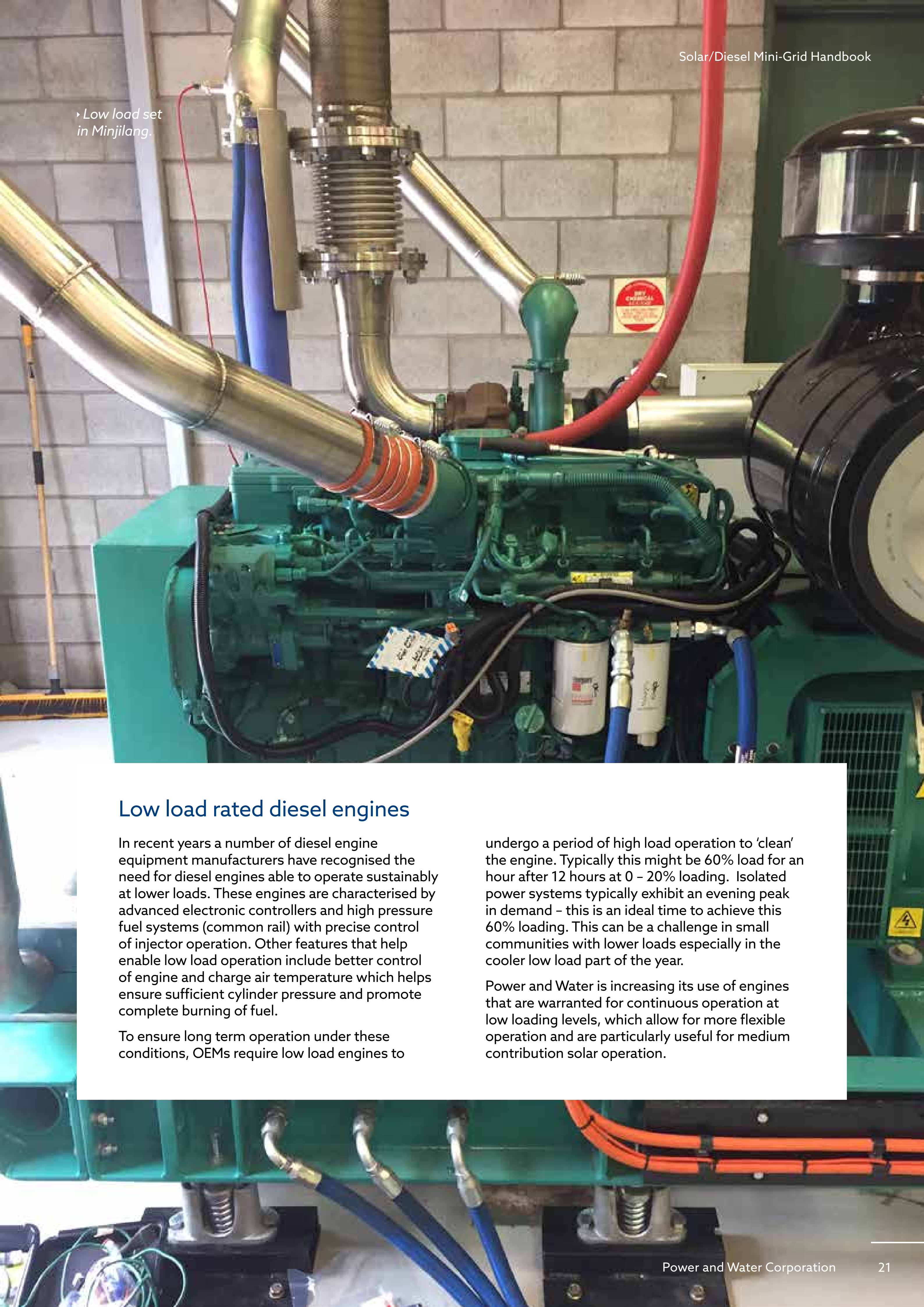
The main disadvantages associated with relying primarily on diesel fuel for remote power generation are the high operational cost of diesel fuel (and diesel fuel transportation) and the risk of fuel price increases including carbon price risk. Diesel fuel is currently the single largest expense for Power and Water's remote community service provision, representing approximately a third of the entire IES remote community operational budget (which covers power, water and sewerage services).

Another disadvantage is the ongoing maintenance requirements of diesel generators. There are limited technical service capabilities available locally in remote communities. Power and Water contract an Essential Services Operator (ESO) in each community to perform basic operation and maintenance of infrastructure, including the power stations. The role of the ESO includes accepting fuel deliveries, recording fuel tank levels, changing the engine oil and maintaining the power station compound. The contractor is responsible to ensure ESOs have the skills and experience necessary for the work, to monitor performance and to provide upskilling as required. Power and Water supports the contractor with this process including through 'train the trainer' sessions.

Two key diesel engine operational parameters are minimum load factor ('minimum loading') and spinning reserve. These parameters have traditionally determined which generator is online. An engine load factor is the current output of the generator divided by its rated capacity. Most engine manufacturers recommend not operating engines for prolonged periods below 40% load factor to avoid violating warranty conditions. Extended operation at low loads ('underloaded') can cause conditions known as 'blow by', 'wet stacking' and 'cylinder glazing' which reduce engine performance and may require premature engine maintenance or rebuilding. Generators typically operate between 50% and 90% of rated capacity to avoid these issues and maximise thermal efficiency.

Spinning reserve is the amount of spare diesel capacity that is online. The spinning reserve setpoint is a control system parameter that sets the minimum value of spinning reserve that must be available online at any time. In practice, for Power and Water mini-grids the spinning reserve setpoint is generally determined by the known highest load in the community that can be turned on at any time. Minimum load factor and spinning reserve parameters have significant influence over the operation of a solar/diesel hybrid system. This is discussed further in Chapter 7 Solar/Diesel Mini-Grids.

Diesel storage tanks in Kalkarindji.



Low load set in Minjilang.

Low load rated diesel engines

In recent years a number of diesel engine equipment manufacturers have recognised the need for diesel engines able to operate sustainably at lower loads. These engines are characterised by advanced electronic controllers and high pressure fuel systems (common rail) with precise control of injector operation. Other features that help enable low load operation include better control of engine and charge air temperature which helps ensure sufficient cylinder pressure and promote complete burning of fuel.

To ensure long term operation under these conditions, OEMs require low load engines to undergo a period of high load operation to 'clean' the engine. Typically this might be 60% load for an hour after 12 hours at 0 – 20% loading. Isolated power systems typically exhibit an evening peak in demand – this is an ideal time to achieve this 60% loading. This can be a challenge in small communities with lower loads especially in the cooler low load part of the year.

Power and Water is increasing its use of engines that are warranted for continuous operation at low loading levels, which allow for more flexible operation and are particularly useful for medium contribution solar operation.

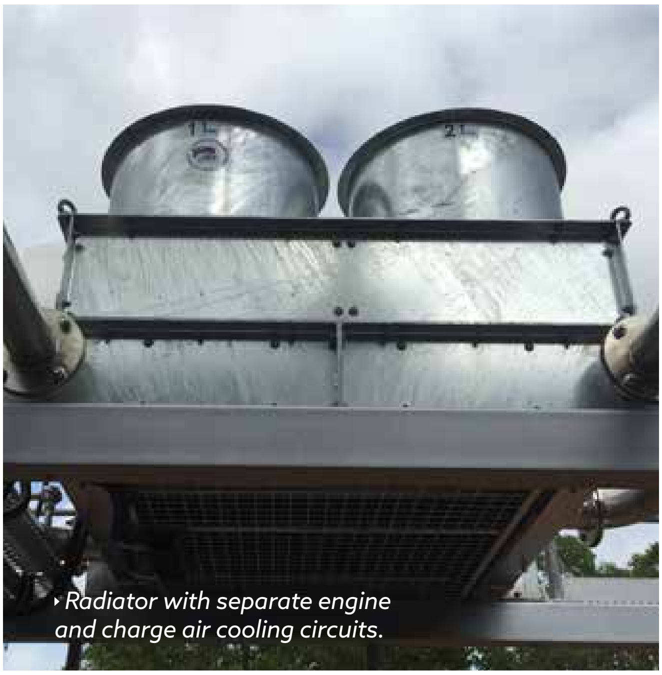
Low load operation risks and remedies

The traditional industry view is that sustained low loading of a diesel engine can result in the following issues:

- 'Blow by' – exhaust gas pressure in the cylinder is not sufficient to seal the cylinder ring. This allows hot exhaust gas to blow by the cylinder ring into the sump. This causes 'cylinder glazing' as oil is baked onto cylinder liners and accumulation of soot/oxidation of sump oil. This can result in the need for premature replacement of cylinder liners.
- 'Wet stacking or slobbering' - incompletely burned fuel and oil accumulates in the exhaust pipework. This can result in leakage around joints in pipework and combustion of the carbon rich deposits in the exhaust pipework. This can necessitate additional maintenance work to clear leaks or artificially load the engine to 'clean' it.

There are a number of ways to monitor for these risks:

- Regular oil testing will highlight symptoms such as oxidation and high soot that indicate that blow by has been occurring.
- Oil consumption records may show that more oil is being consumed. This could occur as more oil is being burned by the engine. This may be caused by glazing which reduced the effectiveness of the cylinder ring wiping action resulting in more oil entering the combustion chamber and being burned.
- Borescope inspection and photography of cylinder condition before commencing low load operations provided a reference point for future condition monitoring.
- Periodic high loading of engines to 'clean' them is a common technique however balancing when to use this technique is not always clear. Some deleterious symptoms such as cylinder glazing cannot always be recovered from if corrective action is taken too late.



Radiator with separate engine and charge air cooling circuits.

Case Study: Minjilang Low Load Diesel Deployment

The remote island community of Minjilang (Croker Island) supports a population of just under 300 people. Power and Water's power station incorporates three diesel generators, with the SETuP program integrating a 100kW utility solar array operating against the 40% minimum loading level of the gensets.

In early 2019 a Cummins QSL9 diesel generator rated at 230kW was installed in order to allow for a higher contribution from the solar array. The manufacturer supports operation of this engine at 10% minimum load setting for extended periods with a requirement for daily loading above 60%.

The engine's high pressure common rail design provides the fine control of fuel injection required for low load operation.

The cooling system developed by Power and Water and its partners has separate remote radiator circuits for engine and charge air cooling. This provides independent control of each circuit's temperature which is also important for effective running at low loads.

The daily high loading requirement for the generator is achieved through normal evening peak loads, however the control system is being reviewed to ensure loading is achieved in all conditions.

6.2 Power and Water Diesel Mini-Grids

Diesel engine sizing

Power and Water has traditionally utilised multiple generator sets of different sizes at each mini-grid power station to best match load to avoid generator underloading and provide redundancy for continuous supply. This is a deliberate design decision in order to service the wide load range that is common in remote Aboriginal communities where significant variation occurs in seasonal (and annual) power consumption. The ratio of peak load to minimum base load in remote communities in the Northern Territory can vary between 3:1 to 5:1 (primarily due to high cooling loads in summer/wet season).

Configuration characteristics:

- Three or four generators with ascending power ratings
- The 70% load point of a small engine ideally corresponds to the 40% load point of the medium engine
- The small size plus medium engine size is usually 125% of the larger engine size, providing (N-1) redundancy in the event that the largest engine fails
- Generators nominally rated to operate between 60% and 80% of their prime power rating, delivering an average load factor of 70% giving optimal life and operation
- Generators are called in turn when the load nears the capacity of the operating set. Similarly the generators change down when the load drops below the 'call-down' set point of the operating set, provided a minimum run time has been achieved to prevent the generation plants 'hunting' the load profile.

A benefit of this approach is that generally only one engine is required at any time (over the entire load range). Operating only one engine (as opposed to two in parallel), reduces the accumulation of engine run hours and therefore minimises O&M costs and potentially delays capital expenditure on engine replacement.

A disadvantage of this approach is that if the small engine fails, it may be necessary to run the medium engine underloaded until the small engine is repaired. This issue is part-mitigated by the community load profile in that typically underloading of the medium engine would most likely only happen overnight (which is when lowest loads are experienced). During the day, when loads are higher, the medium engine would operate closer to its ideal loading and any negative effects from operating at low load (underloaded) the previous night are generally able to be 'reversed' (higher loads help 'clean' cylinder liners).

Alternative Design Approach

One alternative engine-sizing approach is to utilise multiple engines of one size (sometimes two sizes). This approach requires multiple engines to operate simultaneously to serve the load.

A benefit of this approach is that generator call-up scheduling can be optimised to share run hours across similar set sizes or prioritise run hours of particular sets. Another advantage of this approach is that there exists additional set redundancy, reduced parts type count and greater flexibility to schedule maintenance/repairs.

A disadvantage is the additional investment in capital for engines, switchboards, controls and ancillaries. Another potential disadvantage is reduced overall operating efficiency due to the limited matching between load and set sizes that is possible.

In a highly regulated grid, this generator sizing configuration may be preferable or mandated, as this configuration is associated with carrying much higher spinning reserve margins under normal operating conditions.

Diesel engine asset management

Power and Water manages a fleet of more than 180 diesel generators across 51 IES sites, and five minor centres, traditionally utilising the multiple engine size approach described earlier in this handbook. Under its Asset Management Plan, Power and Water manages the replacement and relocation of engines to ensure the generation plant at each community operates within its most efficient range. Power and Water in general standardises remote power stations by manufacturer to achieve efficiencies in serving consumables, holding stock of spares and operator training and support. When new generation plant is required, Power and Water procures engines that incorporate current high efficiency technology that meets international emissions standards.

The asset replacement and relocation approach is changing in response to the increasing availability of low load capable generators, and in response to the SETuP program's hybridisation of over half of its diesel power stations. The purchase of new low load capable engines is being prioritised for solar sites to maximise value from the solar investment. This may result in a mix of different manufacturer's engines at those sites. It may also result in the low load engine carrying a larger proportion of run hours, reducing the replacement period for that set.

7

SOLAR/DIESEL MINI-GRIDS

The overarching objective of implementing solar into an existing diesel mini-grid is to achieve diesel fuel savings to reduce on-going operational costs and diesel fuel price exposure.

This chapter highlights the key benefits, constraints and design considerations associated with implementing solar into existing diesel mini-grids in the Northern Territory.

SETuP in Daly River

7.1 Benefits

The key benefits of incorporating solar into existing diesel mini-grids in the Northern Territory are:

- Solar reduces the kWh that must be generated using diesel fuel, resulting in diesel savings. Note that in Power and Water grids, solar at medium contribution levels does not replace diesel capacity.
- Reduced fuel price risk exposure – diesel fuel price is highly volatile, being affected by global supply constraints and exchange rate movements. Diesel also faces future emissions policy risk. A high reliance on diesel fuel for remote power generation therefore represents considerable and increasing financial risk to Power and Water and the Northern Territory Government. Power and Water mitigates this risk by diversifying the remote community power generation portfolio to include alternative energy sources, such as solar.

Incorporating solar into existing diesel mini-grids may also increase community power supply security. Many remote mini-grids in the Northern Territory are inaccessible for months at a time during the wet season, and rely on stored diesel fuel for power generation. The use of solar to offset diesel fuel consumption may extend the time the stored fuel can last, increasing supply security.

Generating power from solar energy instead of diesel fuel also results in reduced greenhouse gas emissions. Furthermore solar systems are eligible to create renewable energy certificates which can be traded under the Australian Government's Renewable Energy Target. Revenue raised from renewable energy certificates enhances the value proposition of incorporating solar into an existing diesel mini-grid. This financial lever is likely to continue in some form, underpinned by an implicit carbon price.

7.2 Constraints

Introducing solar into an existing diesel mini-grid, particularly at medium to high penetrations, increases system complexity and introduces different risks to the power system which need to be managed. These factors must be considered early in the system design and planning phase, so that appropriate measures can be put in place to ensure the hybrid system delivers the expected results (reduced fuel consumption, increased overall power station efficiency and reduced system cost ($/kWh).

Presented below are five of the key constraints that should be considered for solar/diesel mini-grid design and implementation for remote mini-grids in the Northern Territory. To an extent, these constraints are transferable to most other solar/diesel mini-grid contexts.

7.2.1 Quality of supply requirements

As mentioned, Power and Water has responsibility for the efficient and effective provision of essential services (power, water and wastewater) to remote Aboriginal communities. Power and Water must provide a quality of electricity supplies consistent with national standards and at a minimum:

Nominal voltages:	High Voltage (HV)	11kV, 22kV
	Low Voltage (LV)	240V, 415V
LV variation range:	Steady State	within +6%/-10%
Nominal Frequency:	50Hz	
Frequency variation range:	within 5%; +/-2.5Hz	

Furthermore, the number and length of electricity supply interruptions is not significantly from other communities of similar size and remoteness.

Quality of supply requirements are an important part of solar system design and configuration as strict standards can have a significant cost impact on control and spinning reserve methodology. This is largely due to the risk associated with the intermittent nature of the solar resource. A rapid change in solar output (beyond the power station's available spinning reserve or the response capability of the control system) can jeopardise the stability of the overall power system and cause a total system outage (power station black start). Quality of supply requirements largely determine the ramifications associated with such events, and the extent to which the risks associated with introducing solar into the diesel mini-grid system need to be strictly managed.

Another key consideration in regards to meeting quality of supply requirements is the inertia and step load response capabilities of the online diesel generator(s). Notwithstanding the need for generators to be carrying sufficient spinning reserve to cover solar output during cloud events, the generators must physically be able to 'pick-up' the additional load within a very short timeframe. Applying a large load on a generator in a short timeframe can slow the generator down (low frequency) before the generator overload kicks in. If the generator's step-load capability is insufficient, this can cause the engine to stall. To avoid the generator stalling, the control system can be designed to unload a generator quickly during this event (open a feeder).

Daly River ESO Barry Fletcher in the power station control room

However this may cause a generator to shoot into over frequency (low loading on generator) and shutdown. The careful configuration of the control system to handle these events with minimal impact on the quality and reliability of the community's electricity supply is important. Modern high speed diesel engines with well-tuned electronic controllers are also more capable of handling the variability in PV production.

A further factor is the potential for uncontrolled PV output to exceed the available load, which risks reverse powering the diesel generator resulting in a total system outage and potentially damage to the generator. In the absence of further controls this issue can repeat itself after restoration of the grid. It is also important to note that none of Power and Water's solar projects to date have displaced diesel capacity, i.e. sufficient diesel capacity is retained in order to service the community's entire electricity demand. This is done to ensure the supply security is maintained in the event of evening/night-time peak loads and also throughout the day during cloud events or at times when the solar system is taken offline for maintenance. The business case for the investment in solar (and potentially solar plus BESS) has been based on displacing diesel fuel only (and on minimizing operating costs such as labour and consumables).

Alternative quality of supply requirements:

Across Australia the quality of supply requirements for diesel mini-grids differ according to the level of regulation imposed on the grids. These requirements (e.g. online N-1) influence the design and operation of the mini-grid and may impact the feasibility of a solar/diesel hybrid system.

7.2.2 Legacy Infrastructure

The existing mini-grid infrastructure including the generator capacities, grid network and control system is another key constraint, as explained below.

Existing diesel generators – minimum loading and spinning reserve

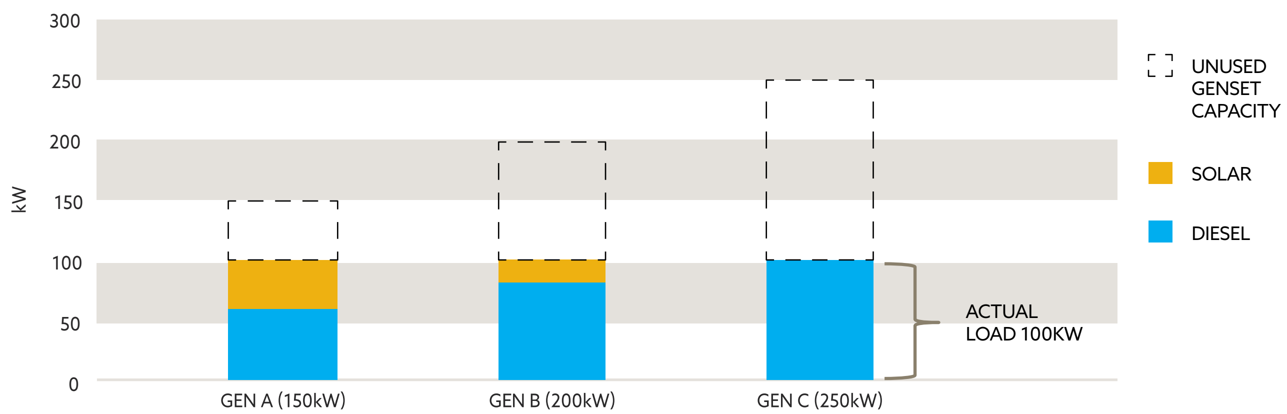
For projects seeking to integrate solar at medium contribution levels, the primary constraint can be diesel engine minimum loading.

As mentioned, diesel engines can be damaged by extended operation at low loads and to avoid this, the minimum loading of diesel engines has historically been between 40% and 60% (of nameplate power rating). This varies depending on engine characteristics such as age, manufacturer, RPM and governor (electronic or mechanical), with many newer models supporting much lower loads for periods of operation.

Due to the fact that a diesel generator must remain online at all times, the minimum load factor represents a portion of the community load that is essentially reserved for diesel generation and cannot be replaced by solar generation. Diesel power systems without supporting storage or other load on demand, therefore have a limited capacity to 'accept' solar. The table and chart below illustrates this point for three different sized generators with a minimum load factor of 40% servicing a 100kW load. Please note this is for illustrative purposes only. The determination of acceptable minimum loading limits on a diesel generator must be assessed on a case-by-case engine-by-engine basis taking in to consideration the engine characteristics outlined above. Furthermore it is important to note that following a period of operation at minimum load, diesel generators may require a period of high loading in order to 'recover' from the effects of low loading.

Example impact of diesel engine size on solar penetration (100kW load):

Generator	Rated Capacity	Minimum Loading (40% load factor)	Net Load 'available' to be served by solar	Resultant solar power penetration (instantenous)
A	150kW	60kW	40kW (100kW - 60kW)	40%
B	200kW	80kW	20kW (100kW - 80kW)	20%
C	250kW	100kW	0kW (100kW - 100kW)	0%



‣ *Diesel engines in the Kalkarindji power station.*

It is crucial that both engine size decisions and solar array capacity decisions consider this relationship. If not well considered, this constraint has the potential to significantly impact upon overall hybrid system economics.

There are several options for solar system design:

1. The solar system size is based on consideration of the existing generators minimum load constraint (i.e. the solar design is modified to suit the generators) or
2. An appropriately-sized generator is installed, in order to achieve desired solar penetration level (i.e. the generators are modified to suit the solar design).
3. A grid-forming BESS is installed alongside a solar array, bypassing issues with the existing gensets through the BESS charging from excess solar and then taking over operation of the mini-grid and going diesel off until discharged.

Note that even with the inclusion of energy storage in solar/diesel hybrid systems to facilitate high penetrations of solar, the minimum load constraint of the existing diesel generators must be able to be respected when online.

Furthermore it is important not to overestimate projected load growth when planning system size and ideal generators sizes, as an oversized system can have suboptimal outcomes for both solar and diesel assets.

Control system and main switchboard

Depending on the scale of the solar system to be integrated into the mini-grid, the existing control system may be another constraint. The solar contribution will determine the extent to which control system modifications are required. Furthermore there may not be room in the existing power station switchboard to connect a solar or BESS feeder, requiring an expensive upgrade of the entire board.

Distributed generation

The existence of Distributed Energy Resources (DER) such as customer-owned rooftop solar is also a key consideration, as remote communities are relatively small and therefore the geographical distance between distributed generation (i.e. customer-owned rooftop solar systems) is insufficient to mitigate or 'balance out' the intermittency of the output of these systems. A cloud event can result is a rapid loss of output from all DER in a system in a shorter timeframe than normal load variation. This is unlike the case in larger grids, where the geographical diversity of distributed solar generation can somewhat reduce the 'net variability' of their output.

In Power and Water's existing diesel mini-grid systems, historically the 'maximum allowable size' of uncontrolled customer-owned solar is the spinning reserve setpoint of the diesel generators. The extent to which the spinning reserve margin is already 'fully allocated' to DER is therefore a consideration for the development of solar/diesel hybrid systems; particularly low penetration systems which seek to avoid the cost of additional 'smoothing' mechanisms such as energy storage.

Case Study: Horizon Power Solar Incentives Scheme

Lombadina community solar installation.

Horizon Power is Western Australia's regional energy provider, operating 38 power systems across 2.3 million square kilometres from Esperance in the south to Kalumburu in the far north.

Horizon Power is investing $15 million in a renewable energy strategy for remote Aboriginal communities – taking them from 100% diesel generation to around 45% renewables. The Solar Incentives Scheme is the first project under this strategy, with Horizon Power investing $1.07 million to co-fund up to 900kW of community-owned solar in eight remote Aboriginal communities.

The scheme was opened to large remote Kimberley communities that are 100% diesel-fuelled, in which solar uptake has been negligible and where the high cost of operations means customer solar PV has the potential to deliver savings to both customers and the utility.

The scheme was co-designed with Aboriginal corporations during 12 months of on-country engagement. Feedback indicated that while communities knew solar would save money, it was expensive upfront, a big technical decision, and they weren't sure who to work with.

From this feedback, Horizon Power created a scheme offering each community a grant (30% capped at $100,000) along with engineering and project management support. Indigenous Business Australia (IBA) was engaged under a partnership agreement, to provide a process for community corporations to access a chattel mortgage should the community seek financing for their solar installations.

Horizon Power's engineers undertook site visits with community members to identify the main community-owned buildings suitable for maximum commercial-scale installations. Horizon Power also drafted detailed technical scopes and undertook an EOI process to determine suitable providers for the communities. This process reduced risk to all parties and removed the key barriers for the communities.

Horizon Power analysis indicated that rather than mandating batteries for smoothing, a utility controlled feed-in management device at the customer's premises would facilitate medium contribution levels at lowest total cost.

The feed in management device was installed by the PV installer as part of installation, and incorporates a secure 3G SCADA connection. Two algorithms are used to curtail the PV when required to:

- Keep generators above minimum load
- Ensure maximum expected fluctuations are less than what the generators can manage.

The power stations in the participating communities operate at N+1 redundancy, meaning there are at least two engines online at all times. This means that there is a large spinning reserve available but potentially higher minimum power station load. No changes to engine scheduling were required to support the solar installations.

The Djarindjin and Lombadina communities were the first participants with 110kW installed in November 2018 across three sites. Performance to date has involved almost no curtailment, and achieves up to 50% solar peak power contribution for the local power system. Simple payback for the customers is expected to be less than five years, with Horizon Power's investment being recouped in a similar period.

7.2.3 Remoteness

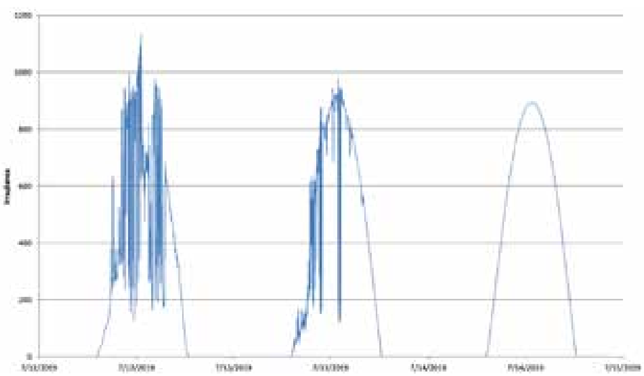
The sheer remoteness of the mini-grids serviced by Power and Water is another crucial consideration when planning and developing a solar/diesel hybrid system due to the costs involved with maintaining infrastructure in remote areas.

There is often limited on-site technical support available for maintenance work on remote power stations and as such there is an additional cost associated with mobilising staff and/or contractors to conduct this work. This should be consideration for solar/diesel hybrid system development as different solar technologies have different O&M requirements, which could significantly impact overall system economics.

7.2.4 Variability (Intermittency)

The integration of solar power into diesel mini-grids can be challenging; largely due to the variability of solar output (during cloud events). In the absence of energy storage, the diesel generator online must cover the customer load that the solar system is no longer able to service during cloud events, i.e. it must ramp up power at the same rate that the solar system reduces power in order to compensate and meet the load. While diesel generators are quick starting, it is not possible to start and synchronise an engine to pick up this additional load in the short time available during such an event. This constraint effectively puts a limit on the total power output of the solar system. Control hardware and software can be incorporated into the system to mitigate this effect by managing solar output depending on the current station operating parameters and spinning reserve available (see 7.3.1 Solar Penetration and Control).

The figure below illustrates solar variability typically seen at SETuP sites.



7.2.5 System Financing

The amount of capital or other financing options available influences the system design and configuration and ultimately the solar energy penetration/diesel fuel displacement achieved. Solar/diesel hybrid system project financial analysis is commonly based on Levelised Cost of Energy (LCOE) and Net Present Value (NPV) calculations. LCOE is conducted on the value of future costs including diesel fuel, operating costs, repairs and maintenance (on both diesel and solar assets) and asset replacement at end-of-life (generators, inverters etc). The sunk cost of existing infrastructure, such as the existing diesel generators and power station infrastructure may be considered in terms of annual depreciation charges or ignored as a baseline.

As mentioned, the solar system design may be constrained by the capacity of the existing diesel generators (see Section 7.2.2). If a decision is made to change or upgrade an existing diesel generator in order to achieve higher solar energy penetrations, this cost must be included in the initial hybrid system financial analysis. Furthermore any integration or auxiliary costs such as control system upgrades or switchboard expansion costs must be considered upfront and included in the financial analysis used for the investment decision making.

TKLN Solar Project: PPA Contract Model - Lessons Learnt

PPA negotiation commenced after the tender was awarded. This process took in excess of 12 months to complete. The tender documents and the PPA clearly allocated risk. The projects were built using fixed price contracts which is the basis of the PPA price. The following lessons learnt have been shared by those involved in the negotiations:

- PPA negotiation may have proceeded more quickly if Power and Water had elected to include the PPA with tender documents.
- Inclusion of diesel operating principles (such as minimum load levels) in the tender documents would have supported design development.
- The relationship of setpoint control to solar ramp rate penalty calculations would have been further informed by a detailed simulation of the systems behaviour had the project timeframe allowed this.
- Solar system performance monitoring whether for PPA purposes or good asset management requires accurate measurement of irradiance.

However, it is very difficult to perfectly model solar output based on a single variable (irradiance). Therefore, in a PPA situation the chosen monitoring solution should be tightly specified with acceptable error tolerance.

Case Study: SETuP remoteness challenges

The SETuP team encountered various challenges relating to the remoteness of participating communities relevant to mini-grid planning:

Safety

- Health services are limited and medical evacuation of employees or contractors may be complex
- Police are often not present in communities and community unrest may occur without warning
- Risk of animals including camp dogs, snakes, buffalos, camels, pigs and crocodiles may be heightened
- Travel risks are higher to due to small aircraft and long distances travelled over dirt roads.

Logistics

- Site inspections and defect rectifications are expensive due to mobilisation costs
- Regular Passenger Transport (RPT) is often non-existent or limited and infrequent
- RPTs have limited baggage allowance and do not guarantee carriage of excess baggage
- Consultations often do not occur on scheduled dates, resulting in repeat visits
- Containers are expensive to return to base and often more than the cost of the container
- Barge costs are high and many communities are accessible by barge only for bulk materials
- Roads are often not all-weather thereby resulting in schedule risks in the wet season

Local restrictions

- Volatile substance limitations are in place in many communities and include petrol and some aerosols
- Alcohol restrictions apply in many communities with severe penalties for non-compliance
- Travel permits are often required and road closures for cultural reasons may be in place

Local capacity

- Local suppliers are limited
- Local specialist labour skills are limited and the use local contractors to rectify defects may not be feasible
- Plant and machinery are very limited and often non-functional or unreliable
- Light vehicles are limited and other transport options are often not available
- Accommodation and food preparation services are limited.

Telecommunications

- Mobile phone coverage is limited and existing services may be intermittent and unreliable
- No internet or email access and a lack of office equipment such as printers and scanners.

Skilled staff

- High turnover of staff due to living conditions and distance from family
- Lack of access to regular amenities and recreational facilities may result in increased cost of labour to retain staff.

Transit damage

- Rough roads require additional consideration of construction methods and packaging
- Barge transport has implications of water damage and requires careful attention.

Waste management

- High cost of disposing of packaging and waste in communities
- Handling of hazardous waste such as oil and paints is problematic.

Implications for future projects

- Ensure comprehensive health safety and environmental plans are in place
- Consider dedicated and experienced logistics personnel with local knowledge
- Leverage experienced remote contractors for their understanding of remote challenges
- Consider additional cost contingencies and float in schedules to allow for unexpected events
- Consider additional spare parts and materials are available on site
- Ensure emergency communications such as satellite phones are in place
- Research local capacity to provide the most suitable accommodation facilities
- Ensure plant and equipment is suitable for challenging transport circumstances
- Ensure compliance with all local requirements such as restricted work areas
- Consider packaging and waste removal or disposal on site carefully.

A barge being unloaded in the remote community of Milingimbi.

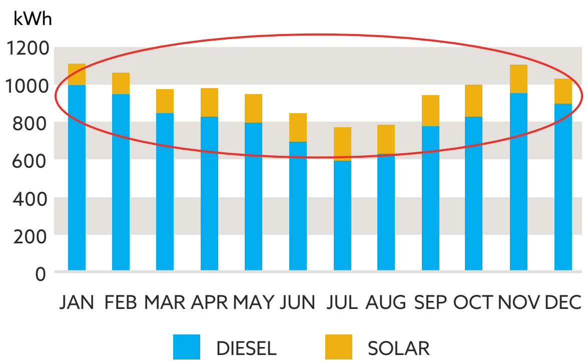
7.3 Design Considerations

As mentioned, the key constraints which influence solar/diesel hybrid system design decisions in the Northern Territory are quality of supply requirements, legacy infrastructure, remoteness and system cost. Presented below are some design considerations in the context of these key constraints. Note that while solar systems are promoted for their modularity, an investigation into the most suitable design for a specific hybrid system is always required on a case-by-case basis.

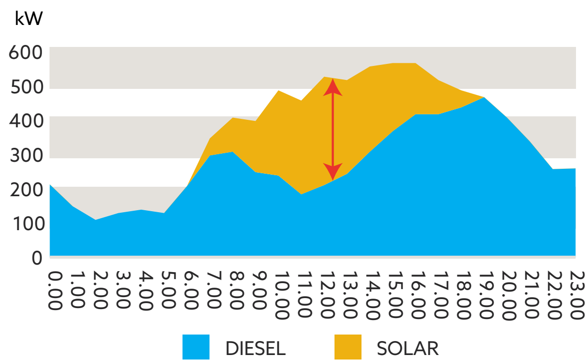
The solar array at Wurrumiyanga on the Tiwi Islands.

7.3.1 Solar Contribution and Control

Solar contribution is typically classified by two numbers: energy fraction and power fraction. Energy fraction (average penetration, [kWh/kWh]) is the fraction of total energy solar provides to the system, which is generally assessed over a fixed period (commonly per year). Power fraction (instantaneous contribution, [kW/kW]) is the fraction of power solar provides instantaneously relative to the total power being provided by all generation sources. These terms are illustrated in the charts below with examples of 15% annual energy fraction and 60% instantaneous power contribution.



- Over the year, solar services 15% of total electricity demand.



- At times solar is servicing up to 60% of the instantaneous electricity demand.

Contribution levels are generally classified as either low, medium or high based on the level of additional engineering required to maintain system stability. With increasing solar contribution comes the need for auxiliary equipment and more complex system control algorithms.

Outlined below is a low, medium and high contribution solar/diesel hybrid system however it is important to note that these terms are not universally defined.

The discussion is focused on utility-owned generation assets and does not consider in detail integration of embedded solar and BESS.

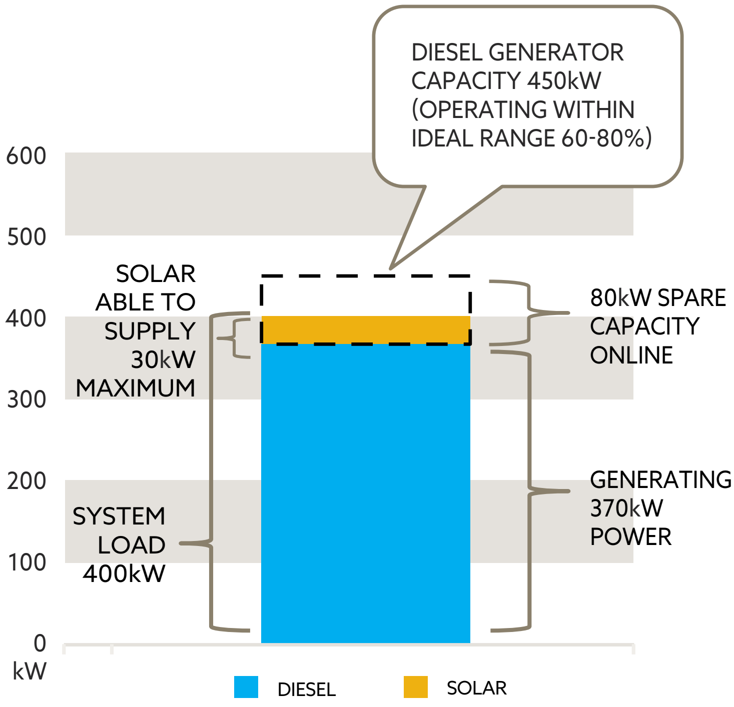
Low contribution

In a low contribution solar/diesel hybrid system, solar capacity is limited to the static spinning reserve margin of the power system (typically between 30kW and 80kW). Low contribution systems are designed so that if the solar output were to reduce from full output to zero output instantaneously, there would be no negative impact on overall power system stability (i.e. the online legacy diesel generator would 'pick up' the additional load within its available spinning reserve). No additional costs are required to provide more spinning reserve or integrated control of the solar output.

As illustrated in the figure below, the contribution level (and therefore diesel fuel savings potential) achievable is severely limited under a low contribution system configuration.

Due to the limit applied to installed solar capacity under the low penetration configuration, a communications link between the solar and diesel systems and controls integration is not required. Grid-connected solar systems at customer premises in remote communities essentially operate as low penetration systems, in the absence of feed-in and curtailment controls.

- **Example Low Contribution System:** 400kW load without integration.



Medium contribution

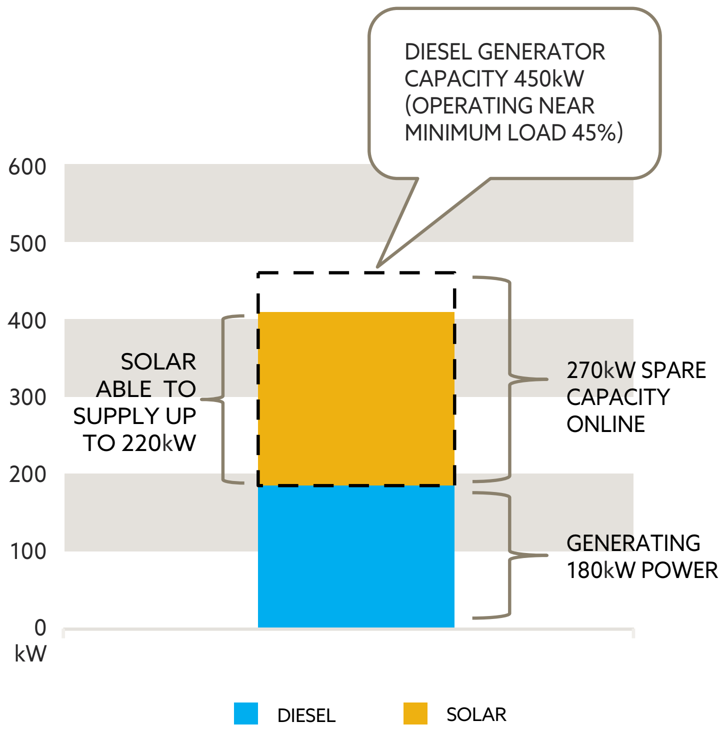
In a medium contribution solar/diesel hybrid system with no energy storage incorporated, control of the solar and diesel system components must be integrated in the power station control system. The control system sends a dynamic set-point signal to the solar system, stating the maximum solar output the power system will accept. This results in the solar output being curtailed at times, reducing its annual output below the optimal available. In determining the setpoint, the control system considers instantaneous power system values including the spare capacity available (i.e. the dynamic spinning reserve) and the minimum load constraint of the online diesel generator(s). The control system operates the diesel generation that would be required to meet the load if no solar were available. This ensures there is sufficient spinning reserve to cover 100% of the solar output in case there is a rapid reduction in solar output (e.g. a cloud event). Voltage and frequency inverter trip settings may also be adjusted as required to maintain stability during transient cloud events.

The renewable energy fraction achievable without energy storage is limited to the window between the system load and the minimum loading requirements of the diesel generators.

Matching the solar output to the load is an important factor, and the use of east/west facing fixed arrays or a tracking system can increase the REF.

The SETuP program has achieved REFs of 15% with generators in the 40% minimum load range, and over 30% where low load capable generators are in place.

- **Example Medium Contribution System:** 400kW load with integration.



- Solar energy contribution can be significantly larger than the 'without integration' case.

Note: this chart depicts a single point in time.

Case Study: SETuP medium contribution rollout approach

SETuP included the integration of 9MW of utility solar arrays into 24 diesel powered communities in the IES program, operating under the principles described in this handbook. Please refer to Appendix 9.2 for a list of the communities and array sizes included in the program.

A key design philosophy was to build free-standing, ground mounted arrays on dedicated leases, rather than attempting to utilise roof space or unused third party land in communities.

Another important design decision was to specify the use of flat plate photovoltaic (PV) technology while allowing the market to identify which PV technology would be most cost effective.

The program specified the use of grid-connect string inverters, with a PV controller at each array to enable the output of all inverters to be managed by the power station control system.

Technical and economic modelling was conducted using the HOMER Pro and ASIM tools to determine the size (kilowatt capacity) of the array that would be optimal for each community, taking into account system loads, landed diesel prices and the existing diesel engine characteristics.

With very little existing land available for the purpose, leases were obtained as part of SETuP. The size of lease required for each community was dictated by the desire to minimise shading from surrounding obstacles and by the larger space requirements of thin film technologies. Once land was obtained, the site was cleared, fenced, interconnected and a solar array built and commissioned.

The overall approach to the project was to minimise changes at each power station, retaining the existing engines as well as modifying the existing control systems. It was important for Power and Water to maintain ownership of the power station control system, so it was not locked into one vendor.

In order to meet data collection and monitoring requirements, all sites had a robust backhaul data connection from the power station to Power and Water's internal supervisory control and data acquisition (SCADA) network. A reliable high speed data connection from the solar array to the power station at each community was also required for real-time control and to support extensive data collection from the solar facility.

The key element of Power and Water's overall approach to the project was not to be too prescriptive, so that designing and constructing the solar arrays was outsourced as an Engineer Procure Construct (EPC) contract using a multi-stage tendering process. This provided the tenderers with some flexibility for innovation and cost savings.

Power and Water retained responsibility for all of the site preparation works, including community engagement, land acquisition, geo-technical assessment, clearing and fencing. Power and Water also designed and managed the electrical and data connections to the Point of Common Coupling (PCC) at each site. This reduced risk during the construction phase for the EPC contractor.

Providing smaller contracts for the site preparation activities also allowed smaller local contractors to be involved in the project.

Power and Water recognised the importance of effective engagement with the Traditional Owners of each community. Community engagement commenced early in the project and continued throughout the program to maximise opportunities for Aboriginal employment and local development.

Solar array at Nyirripi.


‣ *The Daly River PV array during construction.*

High contribution diesel-on

In a high contribution solar/diesel system where the diesel engines remain on at all times, a small energy storage system is incorporated to smooth the solar output during periods of intermittency. The use of energy storage means that the diesel generators are not required to carry additional spinning reserve to cover the entire solar output. During a cloud event the energy storage system provides power for a sufficient period to allow a larger engine to be started which is able to compensate for the reduced solar output. In order for high contribution solar/diesel hybrid systems to work efficiently full integration is required between the solar and diesel control systems.

The TKLN project was an example of a high-contribution diesel-on project.

High contribution diesel-off

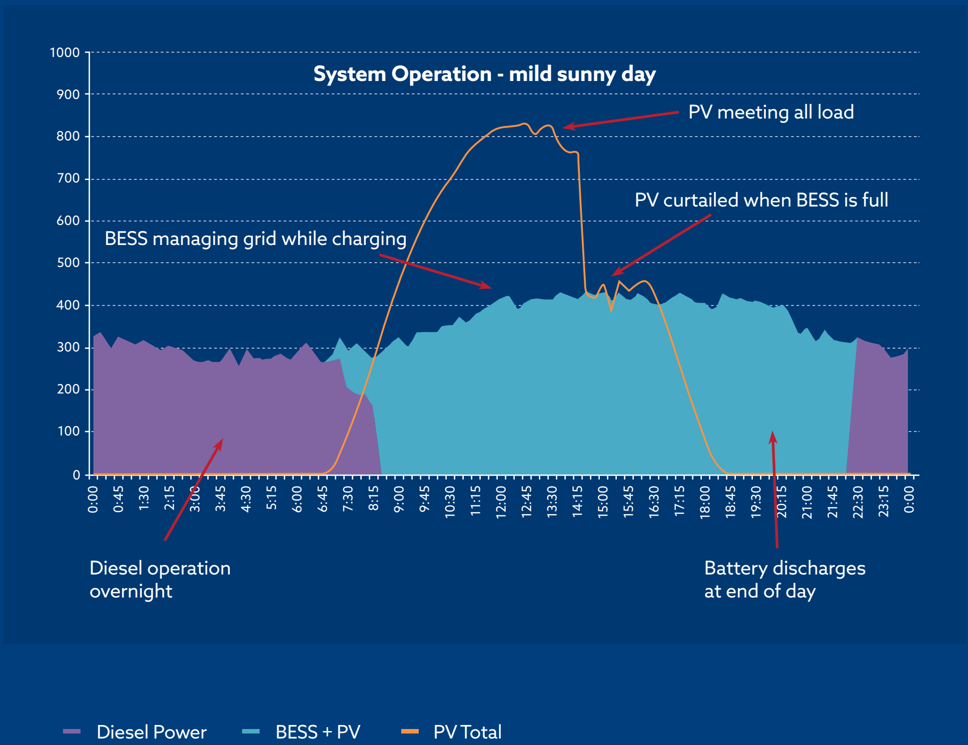
A diesel-off system incorporates a large solar array or arrays and a grid-forming battery energy storage system (BESS). The BESS replaces the services provided by a diesel generator, including frequency and voltage control and provision of fault current. This allows for diesel engines to be shut down once the solar array and BESS can fully meet load, so long as the BESS has sufficient storage to allow for a diesel engine to be called online if solar output drops.

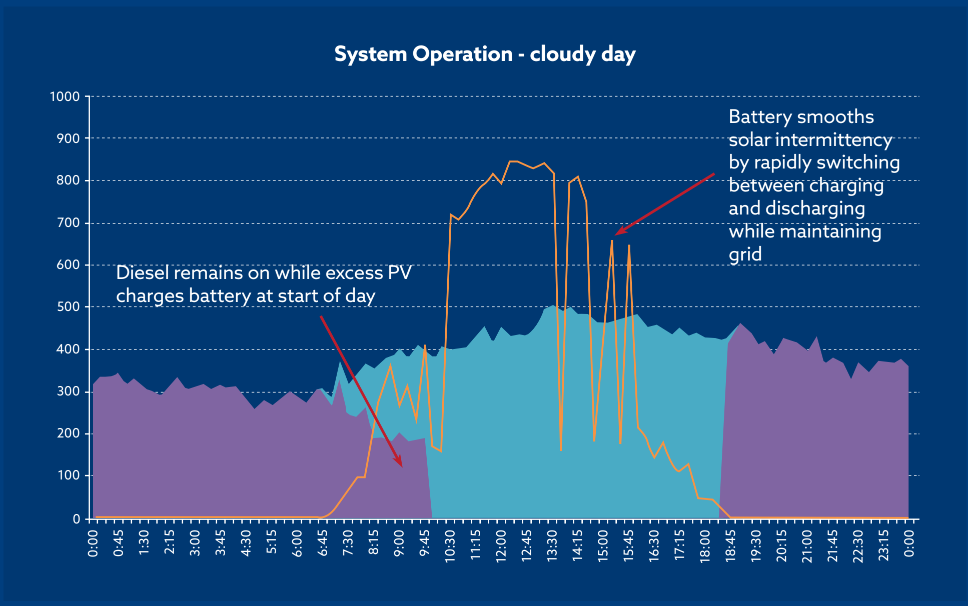
The control system needs full integrated control over solar, BESS and diesel engines, to coordinate scenarios of diesel only, solar/diesel hybrid, and diesel off operation. The solar array still needs to be fully controllable and will be curtailed at times, such as when the BESS is offline, the additional solar output is larger than the BESS available charge rate, or when the BESS has reached its maximum state of charge.

The renewable energy fraction that can be achieved is mainly limited by the economics of solar and BESS sizing and allowance for redundancy. Achieving REFs above around 75% becomes exponentially more expensive.

Case Study: Daly River Diesel-Off High Contribution Operation

SETuP's Daly River project incorporated an 800kVA BESS with a 1MW utility-controlled solar array. The BESS capacity and features allow for solar generation to exceed system load, and for the mini-grid to operate in a diesel off mode once the BESS has sufficient charge. The operating principles are outlined in the figures below.





Case Study: Daly River overview and lessons learned

The SETuP Program's flagship Daly River project incorporated a 1MW solar array and an 800kVA/2MWh BESS into the existing diesel power station. The system was commissioned in March 2018 and operated successfully for its first full year, achieving its target 50% diesel savings for July 2018 to June 2019.

Key learnings from the project included:

The conscious investment in community engagement throughout the project life-cycle reaped dividends in positive community support and minimal complaints despite a number of planned outages required.

The approach taken of seeking external support for development of a detailed BESS specification prior to procurement was viewed as an important part of the project success, particularly for capturing battery life and degradation aspects.

The extreme temperatures of Daly River were a challenge for the BESS cooling system, being conditions that were not replicated during the Factory Acceptance Test and required rework on site to address.

Another challenge that arose during commissioning was ferro-resonance from closing the BESS onto unloaded transformers causing high voltage.

Power and Water chose to manage the control system development in-house, which was important for minimising changes that would impact operational staff. System integration was also kept in-house, and was performed on a live power station. This proved challenging and increased the costs of delays.

Cost savings and improvement opportunities have been captured for the next BESS project.

A final notable challenge was lightning surges into the solar array inverters through the communications cabling. This highlighted the importance of placing surge protectors and/or isolation on all points of entry to the inverters and other sensitive equipment.

Daly River BESS being placed on site.

7.3.2 Solar Resource, Climate and Technology Choice

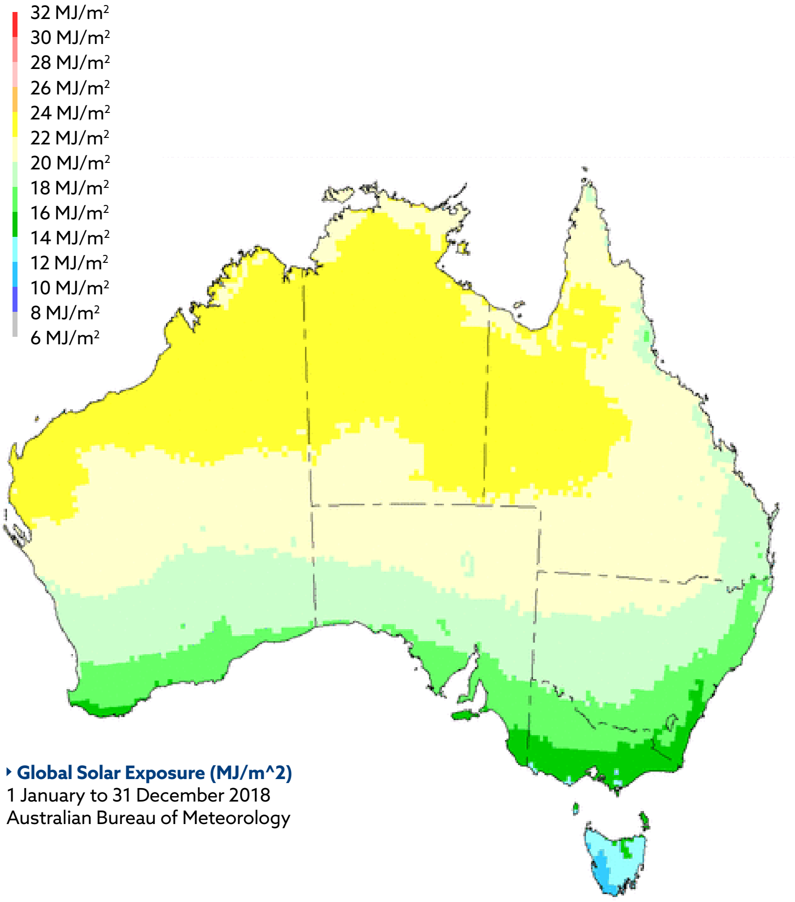
Assessing the available solar resource is a logical first-step when it comes to investigating the potential to implement solar into an existing diesel mini-grid.

The characteristics of the solar resource, the local climate and weather patterns all influence the system configuration design, solar technology choice and system economics and as such having access to good quality, high resolution solar resource data is critical. One minute or one hour solar resource data is sufficient to estimate system performance and economics, however the implications of rapid changes in seconds must be taken in to account in order to appropriately design a hybrid system, mitigate system performance risk and make an informed investment decision. There are many variables that influence the nature of cloud effects (and subsequently the solar resource), which can change significantly within a one minute interval, including local weather patterns, cloud size, frequency, altitude, edge shape and wind speed.

Solar Resource Data

The Australian Government Bureau of Meteorology (BOM) has been measuring a range of solar parameters for decades. One minute solar data is available for 29 locations across Australia. This data includes a range of statistics including global, diffuse, direct and terrestrial irradiance and sunshine-seconds. To find out more go to www.bom.gov.au/climate/data/oneminsolar/about-IDCJAC0022.shtml

The Northern Territory (and indeed most of Australia) has very good solar resources. As shown in the figure below, most of the Northern Territory receives on average up to 24MJ/m² per day.



Global Solar Exposure (MJ/m^2)
1 January to 31 December 2018
Australian Bureau of Meteorology

The Top End of the Northern Territory experiences a tropical climate, with distinct wet and dry seasons. In the wet season (October - April) humidity is very high and it rains frequently; in the dry season (May – September) humidity is relatively low and rainfall is rare. In general the highest community loads occur in the wet season, primarily caused by high cooling loads such as air conditioners.

The southern area of the Northern Territory (Central Australia) experiences an arid climate. Humidity is generally low year-round with short periods of higher humidity immediately preceding the infrequent summer storms. Prolonged high ambient temperatures are often experienced during summer and in winter temperatures at night can drop to below zero. In general community loads are higher in summer however there are winter peaks associated with heating, and overall seasonal variation is not as great as in the Top End.

‣ *Cluster controller in Galiwinku.*

Some solar system technologies and system components can be better suited to particular climates, operating conditions and environments than others.

Furthermore, there are trade-offs between module technology types which must be considered when determining the most appropriate to implement at a specific location. Some of these trade-offs and considerations are outlined below.

Solar modules

All solar module technologies incur increasing losses in module performance as cell temperature rises, due to a drop in open-circuit voltage of the cell. The module temperature coefficient represents the rate of change of module power output as a function of operating temperature. Crystalline silicon solar modules typically have a higher temperature coefficient than thin-film solar technologies; meaning that thin-film technologies are generally better suited to hot climates such as the Northern Territory.

Another consideration is overall module efficiency. Higher efficiency modules (such as mono-crystalline silicon) require a smaller array area to achieve the same output (kWh) than lower efficiency modules (such as polycrystalline modules). Therefore if available land is a limiting factor, high efficiency modules may be preferable. Another benefit of high efficiency modules is that fewer modules will need to be transported, installed, maintained (cleaned) and monitored, resulting in a potential cost saving.

Inverter selection

Features to be considered in inverter selection include: suitability to climate; DC to AC ratio capacity and maximum DC voltage rating; advanced grid interaction and protection features; interaction/interoperability with BESS inverters (diesel-off operation); and ability to provide grid support services.

The solar system configuration including size and number of inverters should also be considered in the context of the remoteness factor. A large number of small inverters (rather than a small number of large inverters), may be preferable so that replacement inverters can be cheaply stored on site. This would mean that if there was an inverter failure, the inverter could be swapped out relatively quickly and easily. Furthermore, this approach would minimise the impact that a single inverter failure would have on overall system output performance. These are important considerations due to the system remoteness, as there may be a delay before an appropriately qualified service technician can mobilise to site. A disadvantage of this approach that needs to be considered is higher efficiency losses and higher complexity in connecting, coordinating and managing a larger number of inverters.

Case Study: Borroloola and Timber Creek

Falling PV module prices are making new solar array designs possible. Building on the learnings from the SETuP program, Power and Water commissioned utility solar arrays for available land at Borroloola and Timber Creek in 2018, with a design brief to maximise the whole-of-life yield from the available space.

This resulted in deployment of pre-fabricated arrays arranged in an east-west concertina configuration, with a 1.4 to 1 ratio of DC to AC capacity. Despite not achieving maximum yield per module, this arrangement was space efficient and resulted in higher output annually than optimal alignment of individual arrays.

It also resulted in a flatter output profile over the course of a day which also improved utilisation of the inverter and interconnection. Importantly, the pre-fabrication significantly reduced time on site for construction, further lowering costs.

Borroloola solar array.

Tracking arrays

The use of tracking arrays might also be considered to maximise the amount of solar output. As mentioned above, one of the key constraints for the communities in which Power and Water operates is that they are often very remote and therefore the value of additional solar generation that can be harnessed using tracking arrays needs to be carefully compared against the additional cost associated with maintaining tracking arrays. Presently for remote applications, the higher O&M costs associated with tracking arrays are often seen to outweigh any benefits in additional solar power generation.

Tracking arrays also potentially increase the risk of solar output intermittency, particularly for the Top End region of the Northern Territory. This is due to tracking arrays' higher system output in the mid-late afternoon, when cloud events are most common. Fixed array solar systems provide a partial hedge to this intermittency, because solar output for these systems is generally highest at midday, not in the mid-late afternoon.

It is important also to review the climate zone for the hybrid system, noting that cyclone-prone regions have additional structural certification requirements which can limit array options.

Other approaches to electricity generation from the sun include concentrating solar photovoltaics (CPV) and solar thermal approaches (solar power towers and parabolic troughs). These technologies are unsuitable to use in remote micro-grids due to their much higher maintenance requirements and very high costs at small scale.

7.3.3 Generators

Two engine technologies – 'low load' and 'variable speed' engines – may enhance diesel engine ability to accommodate increasing the potential solar energy contribution. While these technologies have not seen widespread use, they are under active commercial development and low load engines in particular are seeing increasing deployment. These technologies are outlined below.

Low load diesel engines

As discussed in section 6.1, most diesel engine manufacturers for stationary generation applications. Generally speaking diesel engines can run at low loads for limited durations with negligible effects however on-going operation at low loads can result in engine damage including cylinder 'glazing' and increased 'blow-by'. Operating at low load means less fuel is burned, means reduced cylinder pressure during combustion and reduced energy dissipated. Lower cylinder pressure means the cylinder rings are not forced out to seal the cylinder as effectively. This allows greater 'blow-by' of combustion products into the oil sump. This also means that more oil remains on the cylinder surface. Over time this oil carbonises and the grooved cylinder lining surface becomes clogged with carbon, potentially resulting in premature replacement of cylinder liners.

A small number of remote power system operators in Australia have used diesel engines at low load in wind/diesel and solar/diesel systems for many years, and manufacturers are increasingly making available engines that are designed for longer periods of low load operation. These operate down to very low loads (approximately 10%) but need to be loaded to higher levels at other times to 'undo' the effects of low load operation, using oil sampling to monitor for deleterious effects. Power and Water operational experience to date has demonstrated no increase in O&M costs while achieving high renewable energy penetrations.

Variable speed diesel engines

An alternative way of providing low load operation is to allow diesel engines to operate at variable speeds. Variable speed generator operation is common in large wind turbine systems and the same technology has been employed in diesel engines to allow variable speed constant frequency operation. Power electronics technology allows the diesel engine speed to vary with loading. The power electronics can produce a stable 50 or 60Hz output over a wide range of speeds. The key benefit of this approach is that the deleterious operating conditions of fixed speed low load operation are avoided, ensuring engine longevity. Engine part-load efficiency is improved when speed varies according to load, compared to fixed speed low load operation.

The main disadvantage of this technology is the need for power electronics to convert the variable frequency alternator output into a fixed frequency output. This technology exists but it adds expense and complexity compared to a simple diesel engine – alternator- AVR combination. This also limits the available fault current from the generator. There are a number of companies offering variable speed generators but to date the largest size commercially offered is 125kW, too small for many mini-grid systems.

Fuel delivery at Daly River power station with BESS.

7.3.4 Energy Storage

Energy storage systems can be incorporated into solar/diesel mini-grids to provide a number of different functions. Most-commonly these functions are:

1. To regulate power quality (voltage/frequency/ reactive power) ('short-term energy storage')
2. To smooth the ramp rate of solar output in the event of variability and enable higher power penetration ('short-term energy storage')
3. To shift load to better match solar resource with demand (enabling higher energy penetration) ('long-term energy storage').
4. Combine all the above features to allow diesel-off operation of a micro-grid.

Power quality

Energy storage systems for power quality applications are used to ensure stable operation of the mini-grid when the variability of solar system output is too high for diesel generators to match instantaneous changes. Characteristically in this type of application, the energy storage system has to be able to provide significant amounts of power for timescales on the order of seconds to minutes, and thus relatively small amounts of energy. Effectively this achieves reduced ramp rates on generating equipment both solar and diesel, which limits frequency and voltage excursions that could be detrimental to grid stability.

Ramp rate smoothing

Energy storage systems for load following applications are used to buffer short periods (minutes to hours) of reduced or increased solar energy production and thus can be considered a form of spinning reserve which allows operating with a smaller diesel generator. Effectively this achieves the smoothing of the solar output and supplies a certain level of short-term predictability of solar power available.

Load shifting

Energy storage systems for load shifting applications are used to match peak output of the solar system with peak demand. In high penetration systems this can allow extended operation with smaller (or no) diesel generators.

> Technologies used for energy storage systems can be classified as electrochemical, electrothermal, electromechanical, and electromagnetic; and they can be rated by energy capacity and power capacity. The most common and cost-effective for micro-grids is electrochemical (battery) storage.

There are various energy storage technology types suited to different applications including batteries, pumped hydro, compressed air, super-capacitors and fly wheels. Further information about ESS technology options can be found in Appendix 9.4 Energy Storage Technologies.

The main drivers for the cost of energy storage are cost per unit of storage capacity ($/kWh) and cost per unit of charge/discharge capacity ($/kW). For a good comparison of various storage options it is important to factor in the expected number of cycles the system can undergo before major replacements are required. Thus, depending on system requirements a storage technology may be economically feasible in a low energy, high power application, or vice-versa, or take the middle ground between the two. Only careful assessment can reveal the actual economics of a particular solution under a given use case. Also note that any economic viability must also yield to technical viability for the intended application.

Many different energy storage solutions are offered which can make it quite challenging to choose the correct system for the desired application. In the selection process it is important to determine:

- The desired service the energy storage system will provide. Different types of energy storage technologies are more suited to certain functions. For example, pumped hydro storage is not suitable for power quality applications.
- The energy and power capacities of the energy storage system and whether these are adequate for the intended application. Not all energy storage applications require large amounts of energy. For example in power quality applications the amount of power available is of more significant importance than the amount of energy.
- The expected cycle life of the energy storage system; especially in the case of electrochemical storage devices (i.e. batteries), which have a limited cycle life. Often these devices do not last for the full period used to calculate payback on a solar system and therefore it is important to include replacement cost in consideration of the overall system economics and feasibility. Furthermore the harsh operating conditions

Uterne solar array, Alice Springs.

SETuP technical coordinator Jeff Adams in the Wurrumiyanga solar compound.

of the Northern Territory are such that the manufacturer's design life for the energy storage device may not be achieved.

- The usable energy content. Generally, manufacturers will state the total energy stored in an energy storage system as its capacity. However, this number can be misleading. For example, a lead acid battery that is discharged below about 40% state of charge will have a shortened life cycle. Similarly, a flywheel can only provide power in a given range of speed. It is important to know the amount of available energy for sizing purposes.
- The ancillary equipment required to integrate the energy storage system into the power grid. Many storage devices operate on DC or variable frequency AC power. Thus, additional equipment (inverters, transformer, controls) are required to integrate them into the power grid. This ancillary equipment can make up a significant portion of the overall cost of an energy storage system.
- The maturity of the energy storage technology. While the market is converging on lithium battery technology driven by the emergence of electric vehicles, experience of performance over the long term is limited, and a considerable amount of risk can be involved in choosing energy storage technologies.
- The control and management requirements of the energy storage system. To maximise the technical and economic benefit of an energy storage system it has to be integrated into the overall control strategy of the mini-grid. For this to be possible the behaviour of the energy storage system at all probable charge and discharge states has to be well understood. For example, most batteries will not accept nominal charge current level at a state of charge near 100%.

7.3.5 Modelling Tools

Simulation is an important aspect in the development of hybrid mini-grid systems, due to the complexity involved in the design of such systems. In 2011, IEA PVPS Task 11 undertook a survey to gain an understanding of the hybrid system modelling tools that were used internationally.

Following this investigation, the hybrid power system modelling tools were classified into four distinct types. These are:

1. Dimensioning tools, which calculate system dimensions on the basis of input data (load and climate data and system components)
2. Simulation tools, which use input data to simulate the behaviour of the system over a given period
3. Research tools with a high degree of flexibility and configurability to allow very complete simulation of different systems for research purposes
4. Design tools, which assist with the design of the mini-grid electrical distribution system.

Due to the complexity involved in analysing hybrid mini-grid systems and the vast dimensions of mini-grid design and operation that can be analysed (as demonstrated by the distinct model types above), most software modelling tools are designed for a specific purpose, to investigate a specific aspect of hybrid systems and as such there are strengths and limitations associated with each.

The modelling purpose will largely determine the most appropriate tool to use – RETScreen is good for general dimensioning and preliminary feasibility studies, HOMER for high level economic assessment, PVSyst for detailed technical configurations and Hybrid2 for system analysis. Other characteristics that influence the choice of modelling tool include cost (e.g. free, one-time purchase, annual license or maintenance fees), licencing policy (e.g. open-source, freeware, shareware, commercial), availability (downloadable, available by order, internal use only) and availability and quality of user interface and documentation.

ASIM

To address a gap in available modelling tools, in 2013 Power and Water developed ASIM with ARENA support. ASIM is available to download via the Power and Water website. Supporting documentation including ASIM Reference Manual, Quick Start Manual and Configuration Guide are also available.

The key attributes of ASIM that distinguish it from currently available model tools include:

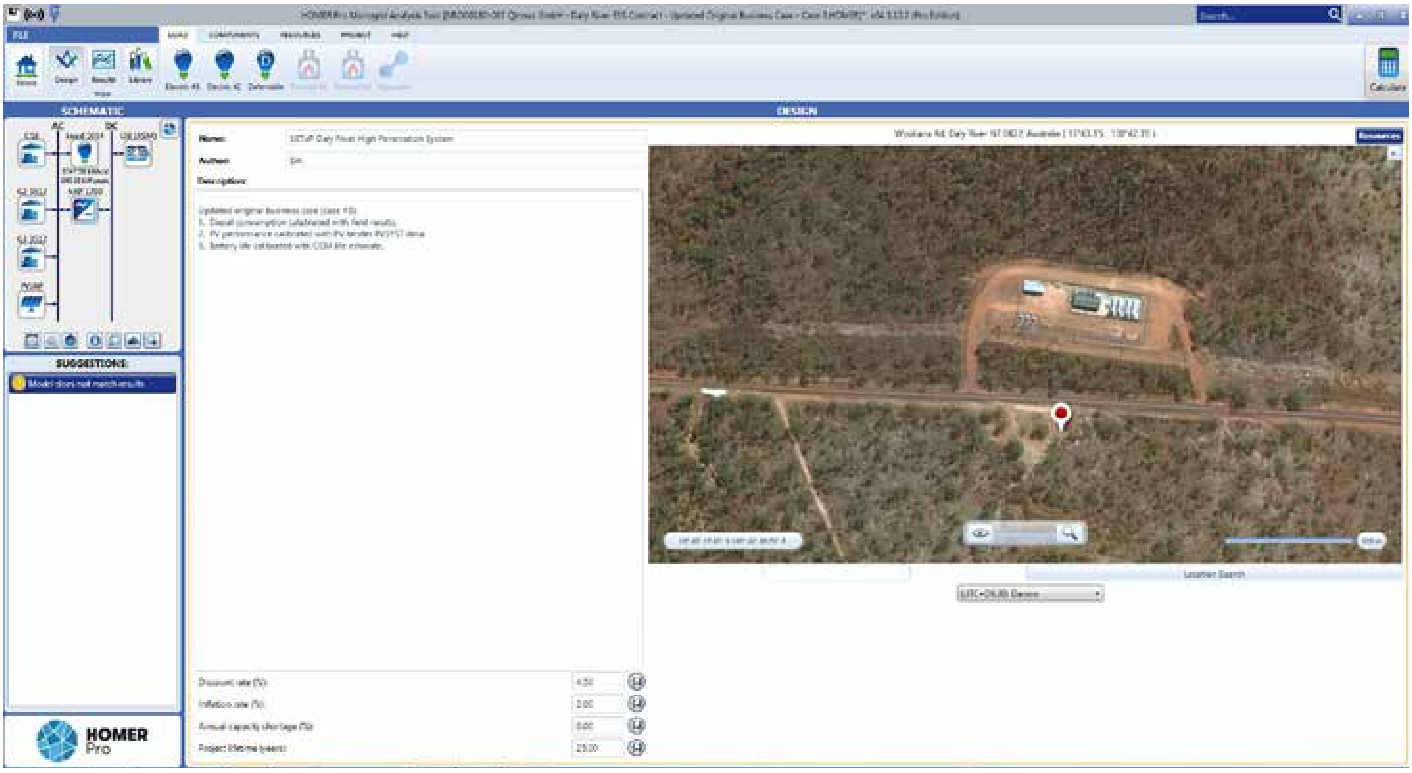
- The control aspect of the model is open source under the GPL V3. This means that users can choose to modify it to simulate their specific power system characteristics (such as generator scheduling), to better match the actual operation of the system being simulated, improving the accuracy of the results
- The model is variable speed not time-stepped
- Typical performance will be one year at one second in less than five minutes
- Based on a compiled and concurrent/parallel implementation rather than an interpreted one, which effects the speed of the model
- Able to be modified with new control methods
- Intended to have a utility view of costs
- Flexible, so economic parameters (such as diesel fuel price) can be escalated
- Conducts one second modelling; therefore will detect system stability issues (e.g. station blackouts) and other transient behaviour at the one second level.

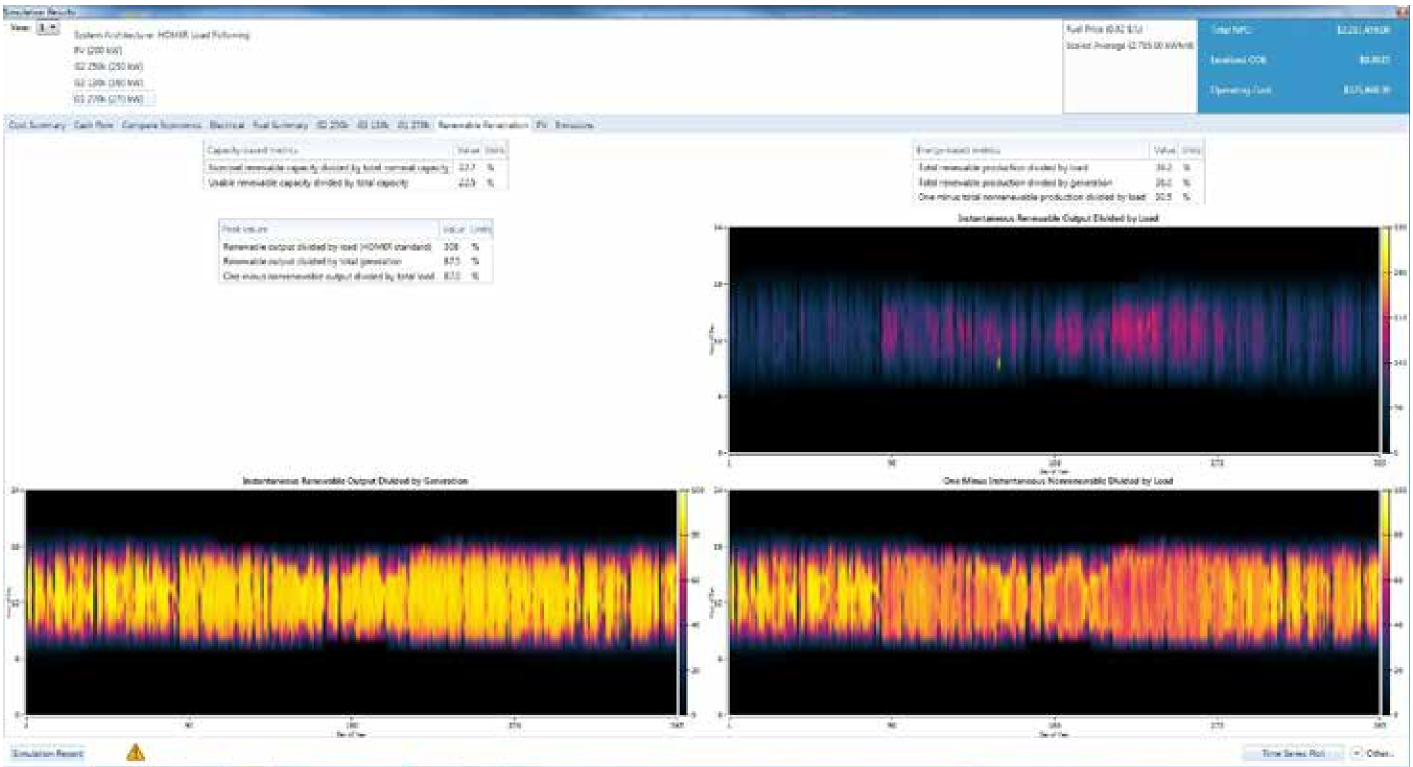
The two distinct ASIM components (Excel spreadsheets and the C# power system model) enable the user to conduct a fast simulation run and then analyse and interpret the data within a spreadsheet. ASIM models hybrid systems on a one second time step however it is capable of generating statistics at a slower rate for analysis. Since ASIM is open source users are able to modify the control algorithms to simulate their particular system, which will improve the accuracy of the results. ASIM has been validated using actual Power and Water mini-grid operation data. ASIM can be used for a range of functions, including:

- Asset management/investment planning
- Whole of life financial analysis PV/diesel hybrid systems
- Spinning Reserve/PV set-point optimisation.

HOMER Pro is a steady-state time-step simulation program that incorporates system optimisation functionality. HOMER simulates the annual performance of multiple system configurations for a specified set of energy sources to find a configuration that satisfies the technical constraints at the lowest life-cycle cost. HOMER allows users to determine sensitivities, such as solar capacity to assist the optimization process. HOMER is available from homerenergy.com.

‣ *Example analysis screens in HOMER Pro.*





7.3.6 Other Factors

‣ *Cloud camera at Maningrida*

Cloud forecasting

Solar PV generation depends on solar irradiance. The relatively unpredictable nature of cloud formation, disappearance and movement causes short-term variability of irradiance levels, resulting in intermittent PV power generation.

This PV generation intermittency results in the sudden ramping-up and -down of the load as seen by the thermal generators. On remote and isolated solar/diesel and solar/diesel/BESS power systems, which lack the diversity of generation found in large interconnected grids, a number of approaches are commonly used to manage this variability.

These include limiting PV connections, curtailing PV output, maintaining a larger spinning reserve of online thermal capacity, and/or relying on the support of alternative generator technologies (e.g. BESS). These factors can be a significant barrier to achieving high renewable power and energy fractions.

Accurate forecasting of the near-term PV performance can be a useful tool for managing variability. Cloud Forecasting Technology (CPT) systems work by monitoring cloud-cover and assessing the likelihood of the PV power generation being affected into the near future (e.g. two to five minutes). The operational decisions that follow from CPT predictions depend on a number of factors including the local climate, the capability of the power system technologies installed, and the constraints imposed on the power system.

In the case of a solar/diesel mini-grid that has capability for direct high-speed control of all generation sources, the scenario for use of CPT is as follows:

- If the CPT predicts no cloud cover into the near future, reducing the spinning reserve may be appropriate given the likelihood of no irradiance fluctuations and smooth PV power generation. This can result in a smaller thermal generator being online. On clear-sky days with a suitable system load, this may result in significant reductions to diesel consumption and/or runtime of more expensive thermal generators.
- Alternatively, should the CPT predict cloud cover to cause irradiance fluctuations into the near future, increasing the spinning reserve by selecting a larger thermal generator can result in foregoing PV curtailment, ultimately reducing diesel consumption and enabling higher renewable energy fractions.
- Consideration would need to be given to the minimum runtime requirements for generators once online to avoid additional wear and tear.

In the absence of integrated high-speed system-wide control, the solar PV rate of change of power, or the ‘ramp rate’, must be limited to a rate that allows another diesel generator time to come online to take up load. CPT can provide the required ramp rate control by pre-emptively ramping down or curtailing PV output ahead of a predicted cloud event. This can be a lower capital cost approach than installing a BESS to provide the required ramp rate control. Alternatively, a CPT and a smaller BESS can be selected to operate in tandem to manage ramp rate.

Some of the major advantages and disadvantages to implementing CPT systems in the context of solar/diesel and solar/diesel/BESS power systems include:

Advantages:

- Potentially enabling higher renewable power and energy fractions to be realised
- Potentially enabling better management of selecting thermal generators to be online which result in reduced PV curtailment, reduced diesel consumption and reduced runtime of more expensive thermal generation
- A relatively inexpensive way of managing system ramp-rates
- Potentially reducing the size of alternative generator technologies required to be installed, such as a BESS, saving on overall capital expenditure.

Disadvantages:

- Additional capital expenditure required to install the CPT system
- A more complex operational system required to incorporate the CPT, including fall-back arrangements for when the CPT is unavailable
- CPT cannot support the situation where PV output exceeds the available system load
- Limited industry experience with the technology.

Currently there are a number of CPT systems operating commercially in both the off- and on-grid space (e.g. Kalkarindji, Karratha Airport, Kidston, Lake Nash, Maningrida and Ti-Tree).

While this technology is receiving increasing amounts of attention in the industry, it is not currently available off-the-shelf and is not proven. For these reasons, studies are currently underway to better understand and quantify the benefits of using CPT systems (e.g. ARENA-funded Northern Territory SETuP cloud forecasting trials, ARENA's short-term forecasting funding round).

Some of the major commercial operators and products within this space are Industrial Monitoring and Control, Fulcrum3D, Meteocontrol, PROAnalytics, Reuniwatt, SolarMatrix, Solcast, and Steadysun.

DER control

The rapid uptake of rooftop solar and potential future adoption of customer battery systems (Distributed Energy Resources) represents both a challenge and an opportunity for diesel mini-grids. Increasing connection applications from customers and supportive government policy mean that simple restrictions on the amount of variable solar on mini-grids are becoming less viable.

Meanwhile, the increasing sophistication of solar inverters and battery systems, and improved access to communication and control technologies has improved opportunities for mini-grid integrated control of DER. Hybridisation of diesel mini-grids in the future will need to consider the uptake of DER by customers alongside utility generators.

Considerations for increasing DER on mini-grids include ensuring the reliability of DER communications and control, specification and enforcement of fall-back settings for loss of DER control, risk management arrangements for the case of sustained loss of DER control and/or DER non-compliance, fault performance, dispatch and control algorithm arrangements, design and implementation of fees, tariffs and connection agreements and islanding arrangements for customers seeking UPS functionality from their DER.

Direct load control

Many of the arrangements and considerations for DER also apply to the potential for implementing direct control over discretionary customer loads. Direct load control is complicated by the difficulty in identifying loads that the customer is willing to allow automated control over by the system controller without notification or case-by-case assent.

Other considerations include the cost of installing required hardware, cost of establishing agreement for the direct control, compliance mechanisms, and fall-back arrangements. There are also risks for utilities when controlling customers' equipment, including the potential need for a switchboard upgrade to meet current standards, the risk that the cause of end-of-life equipment failures are assigned to the utility, and diversity factors of loads compromising the availability of load control when it is needed. Power and Water's assessment is that DER control is more promising technology in small remote hybrid mini-grids.

Volt amp reactive (VAr) Sharing

When solar is added to a diesel mini-grid it is important to consider VAr sharing. A solar generator at unity power factor will in effect reduce the diesel generator power factor. This occurs because the VArs continue to be supplied by the diesel generator while the diesel share of kW decreases. The net effect is a power factor reduction. Generally speaking, alternators can operate with low (<0.8) power factors as long as they are lagging and assuming that the generators are not fully loaded. Of greater concern is a leading power factor. Alternator voltage regulators (AVRs) cannot regulate voltage with anything but a very small leading power factor. Refer to the figure below for typical AVR stability regions.

Ideally the solar generator and the diesel generator share VArs proportionally. In the absence of reliable inverter power factor control, it may be tempting to fix the inverter power factor to a nominal value such as 0.9 lagging. This should be done with care. If the load power factor approached unity, then a fixed inverter power factor could force the generator power factor to lead and risk stability. The greater the solar penetration, the greater the risk that a fixed lagging inverter power factor will cause stability issues. Unless this risk can be negated then a unity solar inverter power factor is recommended, as has been used for the SETuP program.

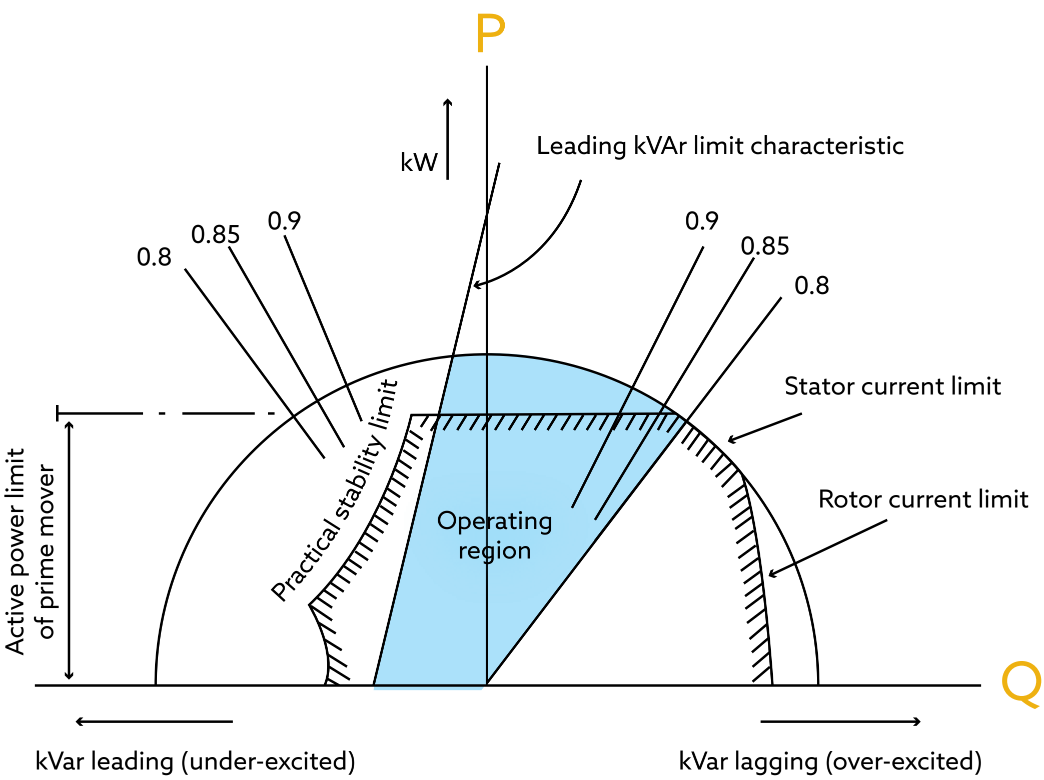
Collaboration and change management

Incorporation of solar technologies into existing diesel power systems requires building trust and managing change. Investment must be made into people, training, and change management alongside project delivery.

In high technology projects where imperfect information exists, a collaborative approach is an effective way to hedge against uncertainties. Collaboration throughout projects delivery will build good will and a common vision for the project's success.

When project challenges arise, as they do in innovative projects, a collaborative approach ensures all parties work to find a mutually acceptable solution.

› *Typical operating region of a generator.*



8 CONCLUSION

The remote energy landscape has shifted significantly since the first edition of this handbook was released. Solar and battery costs are falling rapidly against diesel prices. Diesel engine manufacturers are modifying their offerings to recognize the imperative of supporting higher levels of solar integrations.

Projects such as SETuP are making solar arrays 'just another generator' in mini-grids, and the Daly River project has successfully piloted a mini-grid regularly operating solely on inverters, without synchronous diesel generation.

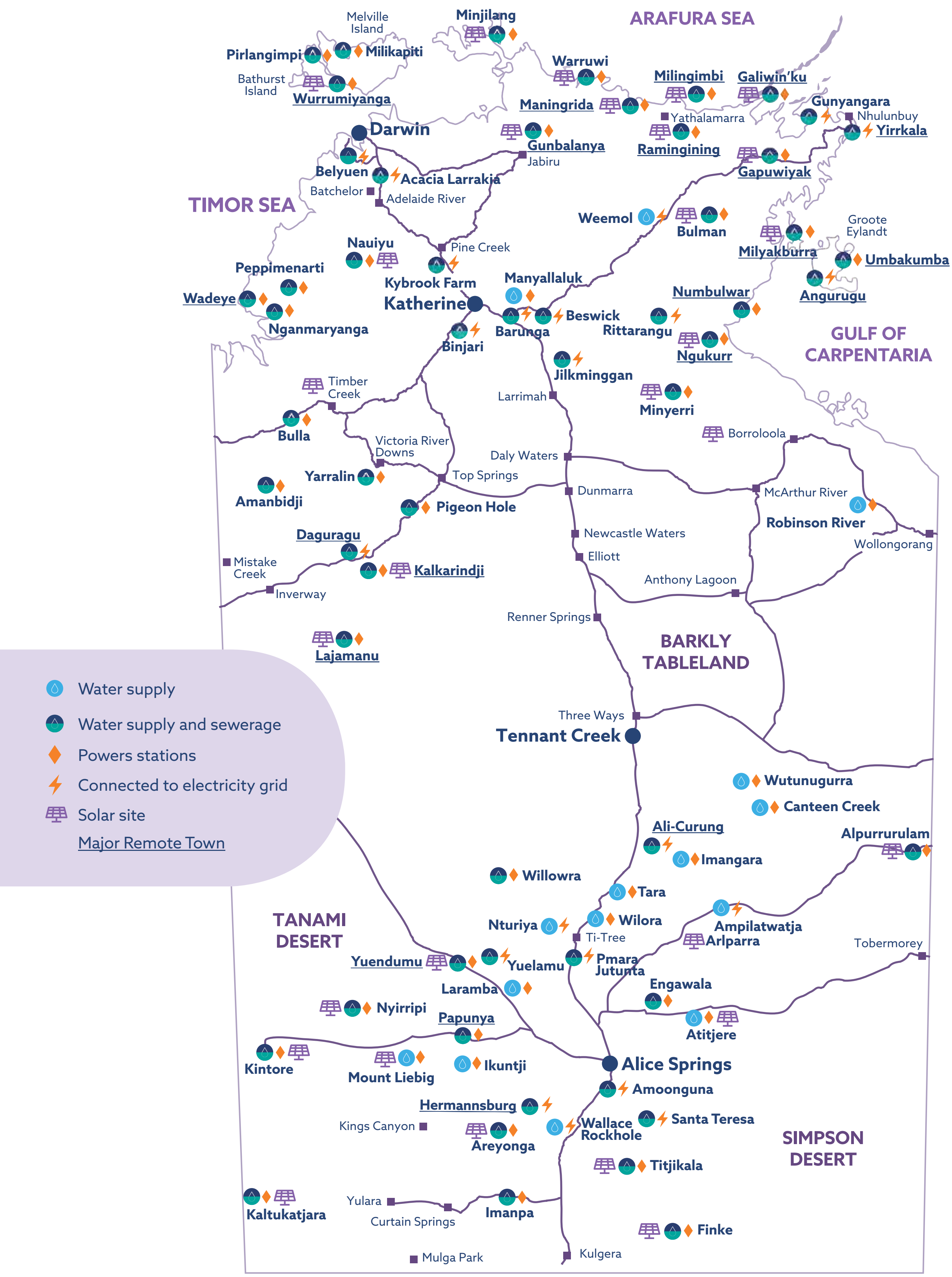
Given the changing economics and emissions reduction targets, the future will see more BESS deployments, with diesel generation moving to a backup and reserve role. The integration of increasing levels of customer owned solar is the next frontier for remote mini-grids that will drive smarter grids with more storage. Power and Water hopes to update this handbook in future to incorporate industry lessons learnt through this transition.

Nauiyu community elder Mark Casey at a barbecue to welcome the Minister of Essential Services to the solar farm.

9 APPENDIX

Contractors at work installing the solar arrays at Daly River.

9.1 Remote Aboriginal Communities Serviced by Power and Water



9.2 Utility Scale Solar/Diesel Mini-Grids in Australia

Presented below is a brief list of operational utility scale solar/diesel mini-grids in Australia.
Note that some of these systems are owned by a third party, not the utility.

Utility	Location	Solar System Capacity (kWAC)	Technology	ARENA funded?
Territory Generation	Kings Canyon, NT	225	Flat plate, fixed array	
Territory Generation	Yulara, NT	1800	Flat plate, fixed array	Yes
Power and Water Corporation	Kalkarindji, NT	402	Flat plate, fixed array	
Power and Water Corporation	Lake Nash (Alpurrurulam), NT	266*	Flat plate, fixed array	
Power and Water Corporation	Ti Tree, NT	324	Flat plate, fixed array	
Power and Water Corporation	Borroloola, NT	400	Flat plate, fixed array	
Power and Water Corporation	Timber Creek, NT	125	Flat plate, fixed array	
Hydro Tasmania	King Island, TAS	470*	Flat plate, fixed array	Yes
Hydro Tasmania	Coober Pedy, SA	1000*	Flat plate, fixed array	Yes
Hydro Tasmania	Rottnest Island, WA	600*	Flat plate, fixed array	Yes
Hydro Tasmania	Flinders Island, WA	200*	Flat plate, fixed array	Yes
Horizon Power	Nullagine, WA	200	Flat plate, single- axis tracking	
Horizon Power	Marble Bar, WA	300	Flat plate, single- axis tracking	
Horizon Power	Meekatharra, WA	455	Flat plate; fixed array	
Horizon Power	Degrussa Copper Mine, WA	10600	Flat plate; single-axis tracking	Yes
Ergon Energy	Doomadgee, QLD	264	Flat plate, fixed array	Yes
Ergon Energy	Weipa, QLD	1200	Flat plate; fixed array	Yes
Ergon Energy	Cannington Mine, QLD #	3000	Flat plate; fixed array	

* These hybrid mini-grid systems also incorporate wind power
# This is a solar/ gas hybrid off-grid system

Weather station in Titjikala.

Power and Water Corporation communities that are part of the Indigenous Essential Services (IES) program and that received flate plate fixed arrays at diesel power stations as part of the Solar Energy Transformation Program (SETuP):

Community	Solar System Capacity (kWac)
Apatula (Finke)	100
Areyonga	100
Arlparra	450
Atitjere (Harts Range)	225
Bulman	100
Daly River (Nauiyu)	1000
Galiwinku (Elcho Island)	750
Gapuwiyak (Lake Evella)	425
Gunbalanya (Oenpelli)	675
Kaltukatjara (Docker River)	100
Walungurru (Kintore)	225
Lajamanu	400
Maningrida	1,175
Milingimbi	425
Milyakburra (Bickerton Island)	100
Minjilang (Croker Island)	100
Minyerri	275
Mt Liebig (Amunturangu)	50
Ngukurr	400
Nyirripi	200
Ramingining	500
Titjikala (Maryvale)	400
Warruwi (Goulburn Island)	175
Wurrumiyanga (Nguiu / Bathurst Island)	1075
Yuendumu	500

9.3

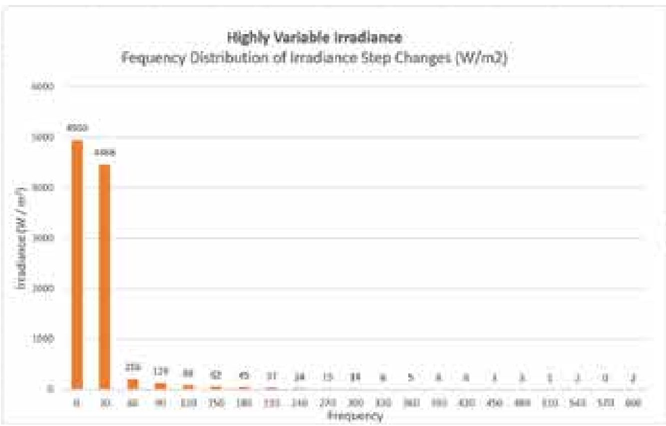
Distributed Generation - Alice Springs Investigation

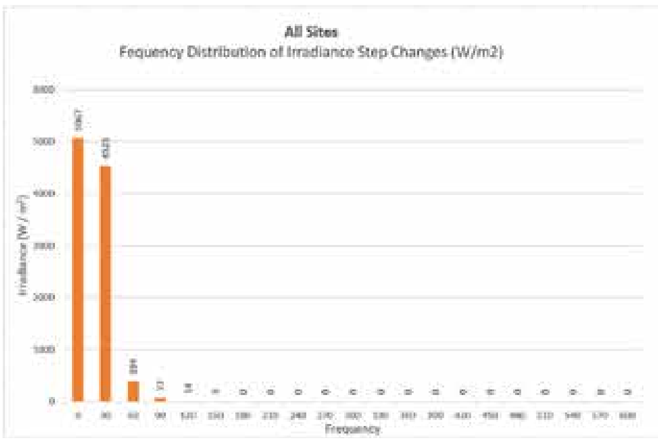
PV generation is entirely dependent on the level of solar irradiance. On a clear sky day, solar irradiance and therefore PV generation follows a predictable pattern. However, on cloudy days, solar irradiance at ground level will be impacted by moving clouds and as a result PV generation will be equally variable. The potential impact of this irradiance variability on the stability of electricity grids with moderate penetration PV generation was assessed as part of an ARENA supported research project in 2013-2014. The project commissioned nine individual weather stations distributed across the wider Alice Springs region, with locations chosen specifically to be within a 15km radius from the central site at the Desert Knowledge Australia Solar Centre (DKASC).

This study measured the step changes in irradiance (W/m2) at five second intervals. It observed that on clear sky days these step changes typically fall in the range of 0 -30 W/m2.This equates to potential step changes in PV generation at the site of 0-2%.

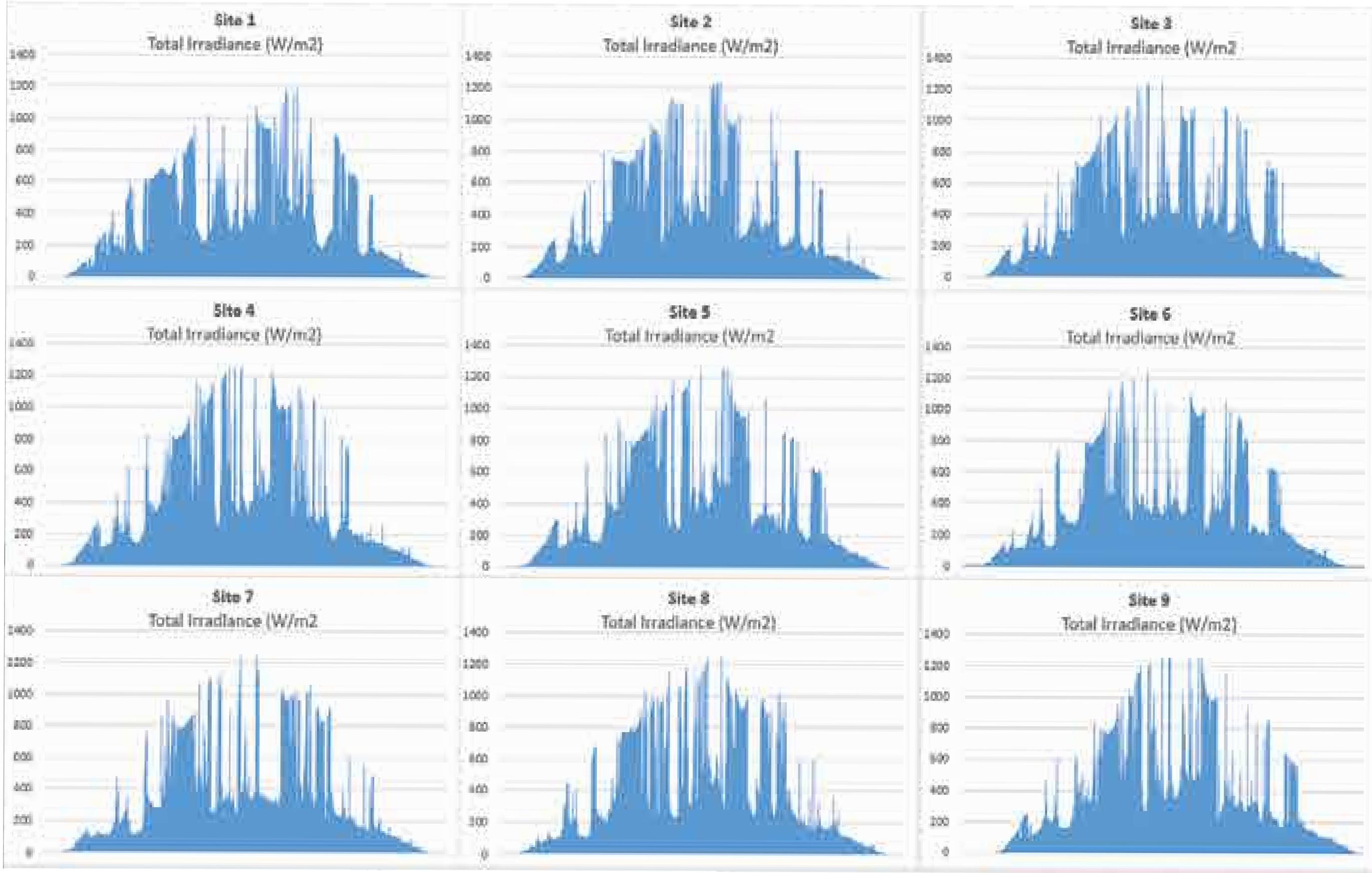
On cloudy, highly variable days, step changes in irradiance were significantly greater, and at times in excess of 500 W/m^2. This equates to potential step changes in PV generation of up to 50% to 60% for a single location. However, when all nine geographically dispersed sites were examined and the irradiance of the nine sites aggregated, a significant drop in step variability could be achieved, with the largest step value on highly variable days generally observed to be less than 150 W/m2 overall.

The key conclusions of this study was that, like many other remote and regional grid networks, the Alice Springs grid already tolerates a high level of load side variability without compromising on operational outcomes. Additionally, stability issues caused by irradiance variability (and therefore PV generation) can be significantly mitigated against through the geographical dispersion of PV generation throughout the physical grid network.

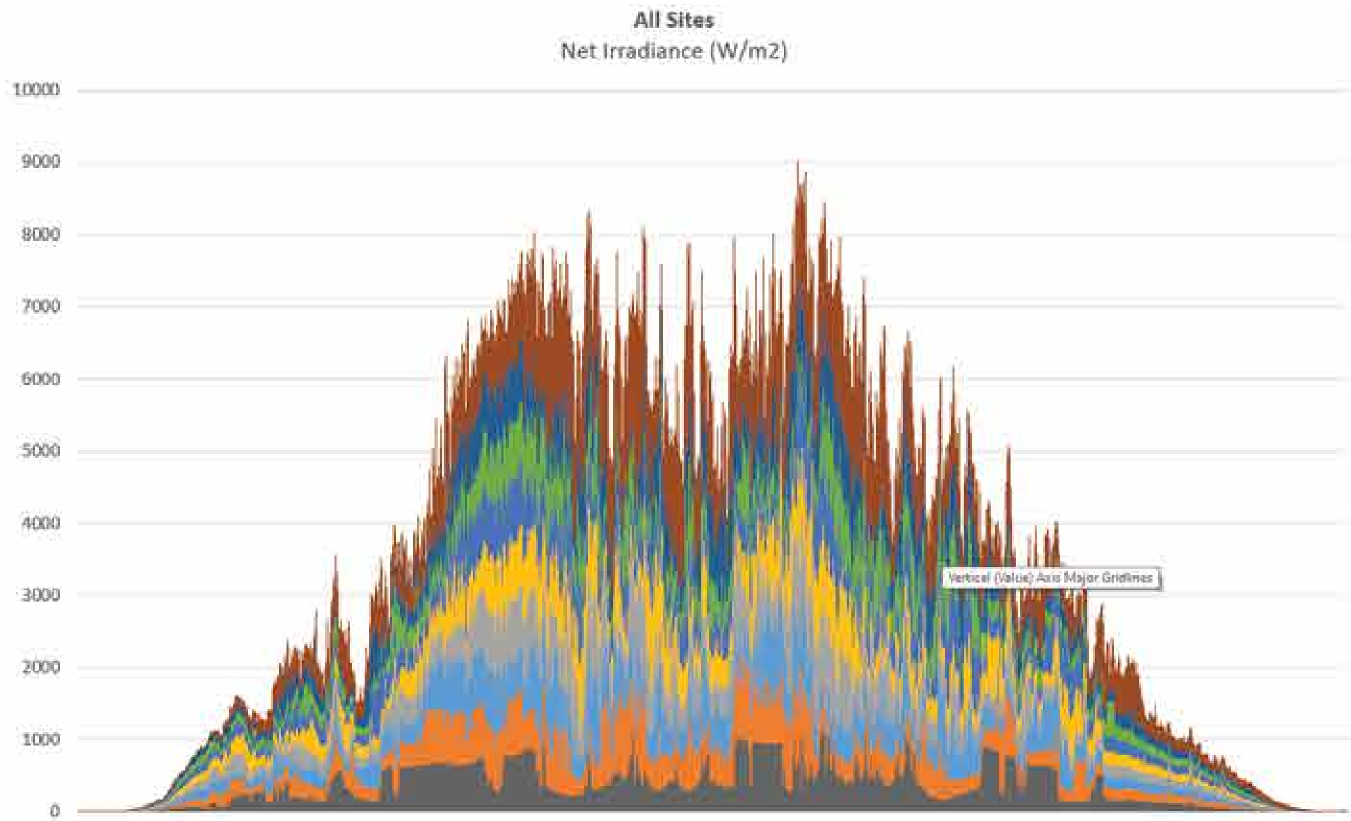




Frequency distribution of irradiance step changes for one site compared to the sum of all sites - demonstrating the reduced incidence of large step changes for the combination of sites.



‣ *Solar insolation across individual sites in the Alice Springs region.*



‣ *Net irradiance for combination of all sites.*

9.4 Energy Storage Technology

Battery Energy Storage Systems (BESS) are diverse technologies and can be broadly grouped as follows:

- Electrochemical
- Electrothermal
- Electromechanical
- Electromagnetic

While it is a rapidly changing field, the information provided below provides a reasonable summary of current technologies.

Electrochemical

Electrochemical storage has seen rapid advancement over recent years and is the most common type of storage solution selected for both off-grid or mini-grid functions.

Lead acid batteries

Deep-cycle lead acid batteries have traditionally been the most commonly used storage system for remote area applications. As an established technology, these batteries are well understood, have good tolerance to high temperatures, a certain degree of inbuilt resilience and require less stringent operating conditions. In comparison to most newly developing technologies, traditional lead-acid batteries have a lower energy density (therefore require more space), have less sophisticated operating strategies and have not seen a considerable price reduction over time. The development of new advanced lead acid battery systems is seeking to overcome some of these disadvantages.

Lithium ion batteries

With significant price reductions over recent years, and high energy density, lithium ion batteries are becoming an increasingly prevalent and cost-effective energy storage solution. Lithium ion technologies have a good tolerance for high discharge cycles, but do require operation within a limited temperature range, therefore heating / cooling mechanisms should be considered for most operating locations. They are widely viewed, at least in the medium term, as the technology most likely to take over from lead acid as the primary source of electrochemical storage and have begun to be installed at quantity in both large on-grid and off-grid applications.

Flow batteries

A variety of chemistries for flow batteries are also currently under development. Some key advantages of flow battery technologies include the ability to completely discharge without affecting cycle life, and the elimination of capacity degradation over time. Demonstration of this technology on any significant scale is limited and it should still be viewed as an emerging technology.

Comparison of key features – Electrochemical Storage Technologies

	Lithium	Advanced Lead Acid	Lead Acid (VRLA)	Flow
Energy density	High	Moderate	Low	Moderate
Typical degradation	Depends on cycle regime.	Dependent on temperature and discharge cycle.	Heavily dependent on temperature and discharge cycle.	Zero degradation for the life of the battery.
Typical discharge vs cycle life	Typically 20% loss of capacity after 10 years.	Significantly improved over traditional lead acid.	Poor life at high discharge regime.	Can be fully discharged without affecting cycle life.
Typical efficiency	Tolerant to high discharge, but cycle life is affected by depth of discharge.	90%	70% – 80%	80%
Operating temp range	90%	Up to 50°C	Tolerant to high temperatures, but longer life if below 25°C	Up to 50°C

Diesel tank in Maningrida.

Electromechanical:

Flywheels can be categorised into traditional steel rotor, low RPM flywheels and composite rotor, high RPM flywheels. Due to their long cycle life, fast response and high power levels, flywheels are superior to electrochemical BESS in power quality applications but generally unsuitable for load shifting applications.

Compressed air energy storage (CAES) systems are usually large-scale, and generally make use of the underground caverns of abandoned mines. The systems operate using compressed air, stored under constant pressure, with the ability to charge and discharge as required. In February 2019, ARENA announced that funding had been approved to develop Australia's first CAES facility, re-purposing the Angas Zinc Mine in Strathalbyn, SA.

Pumped Hydro BESS are traditionally considered the most cost-effective large-scale energy storage systems available, however, this is generally limited to systems larger than several MW in capacity. Pumped hydro-electric power operates on the potential energy difference between two water reservoirs at different elevations. Elevation difference and reservoir volume have to be of significant size for such systems to provide viable ESS options. Thus, these systems rely on the availability of local or regional geographical features which are not available in many locations.

Electromagnetic:

Electromagnetic BESS, supercapacitors and superconducting magnetic energy storage (SMES) are highly efficient, but also very expensive as they rely on highly specialised materials. Subsequently, their application is generally limited to small storage functions, usually for power quality applications.

Electrothermal:

Unlike the other BESS described above, most thermal BESS are not intended specifically for delivery of electricity services, but rather the delivery of stored thermal energy for services that would otherwise be met by the use of electricity. These thermal systems either store heat or cold to be released later for direct temperature uses, or to drive industrial processes. Electrothermal heaters usually employ bricks or water as the energy storage medium; and electrothermal cooling systems use chilled water or ice. Electrothermal storage that is specifically designed to deliver electricity to a grid or network is only available at this time for large scale applications that utilize arrays of reflecting mirrors focused to a single point to heat salt to a molten state and then release this heat at a later stage to create high pressure steam, to drive turbines to generate electricity. Typically, these systems are only deployed on scales above 50MW.

In addition to these technologies, there are a multitude of new technologies currently under development or emerging within the marketplace. Of these, the most prominent are the hydrogen-based systems that generate hydrogen for energy storage and utilize fuel cells as the means of converting the stored hydrogen to electricity. Hydrogen based storage is becoming a promising energy storage technology, with a number of well-known international companies currently working to demonstrate the capability of such storage systems on a large scale.

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