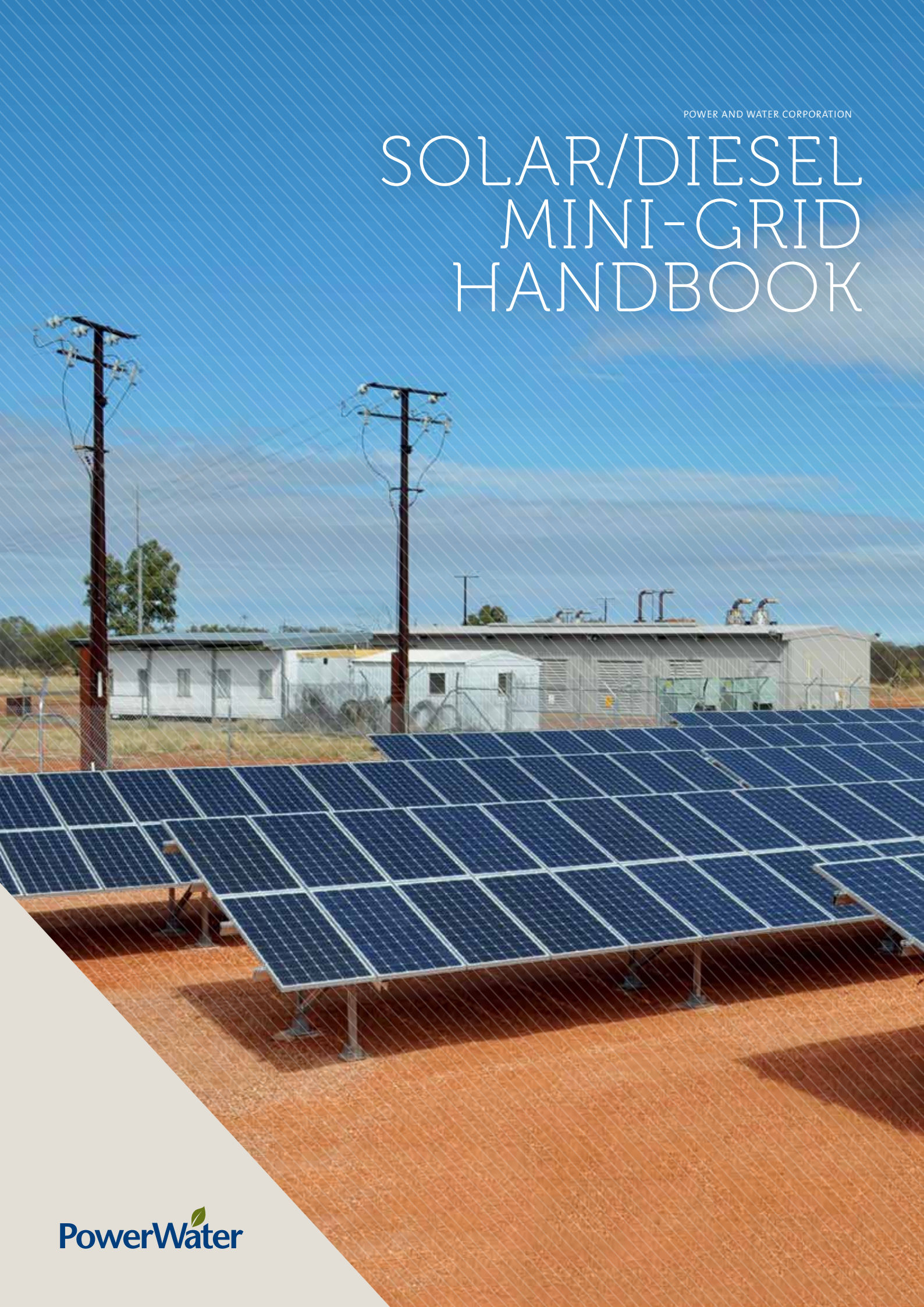
POWER AND WATER CORPORATION

SOLAR/DIESEL MINI-GRID HANDBOOK



PowerWater

ARENA

Australian Government

Australian Renewable Energy Agency

This project is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA). ARENA is an independent agency established to make renewable energy technologies more affordable and increase the amount used in Australia. ARENA is supportive of all renewable energy technologies and invests along the innovation chain – from research in the laboratory to large scale technology projects, as well as activities to capture and share knowledge. More information is available at www.arena.gov.au.

PowerWater

Power and Water Corporation (PWC), 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 Indigenous communities and 66 outstations across the Northern Territory (NT). To service these communities, PWC operates over 50 isolated mini-grid power systems, most of which rely on diesel fuel for power generation.

Electricity demand in remote NT communities is continuing 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 highly volatile, being 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.

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

PWC has an over 20 year track record of owning and operating solar/diesel hybrid systems in remote Indigenous communities. There are currently eight solar/diesel hybrid systems servicing eleven communities. These incorporate a range of solar technologies including concentrating photovoltaic dishes and flat plate solar systems with an installed solar capacity of over 1.7 megawatts. PWC is pursuing a step-change in its remote generation portfolio, with the hybridisation of the entire diesel mini-grid fleet to include solar.

PWC 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

BOM – Bureau of Meteorology

CPV – Concentrating Solar Photovoltaics

CSO – Community Service Obligation

ESO – Essential Services Operator

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

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

NT – Northern Territory

NTG – Northern Territory Government

O&M – Operation and Maintenance

PPA – Power Purchase Agreement

PWC – Power and Water Corporation

RPM – Revolutions per minute

SCADA – Supervisory control and data acquisition

TKLN – Ti Tree, Kalkarindgi, Lake Nash (TKLN Solar Project)

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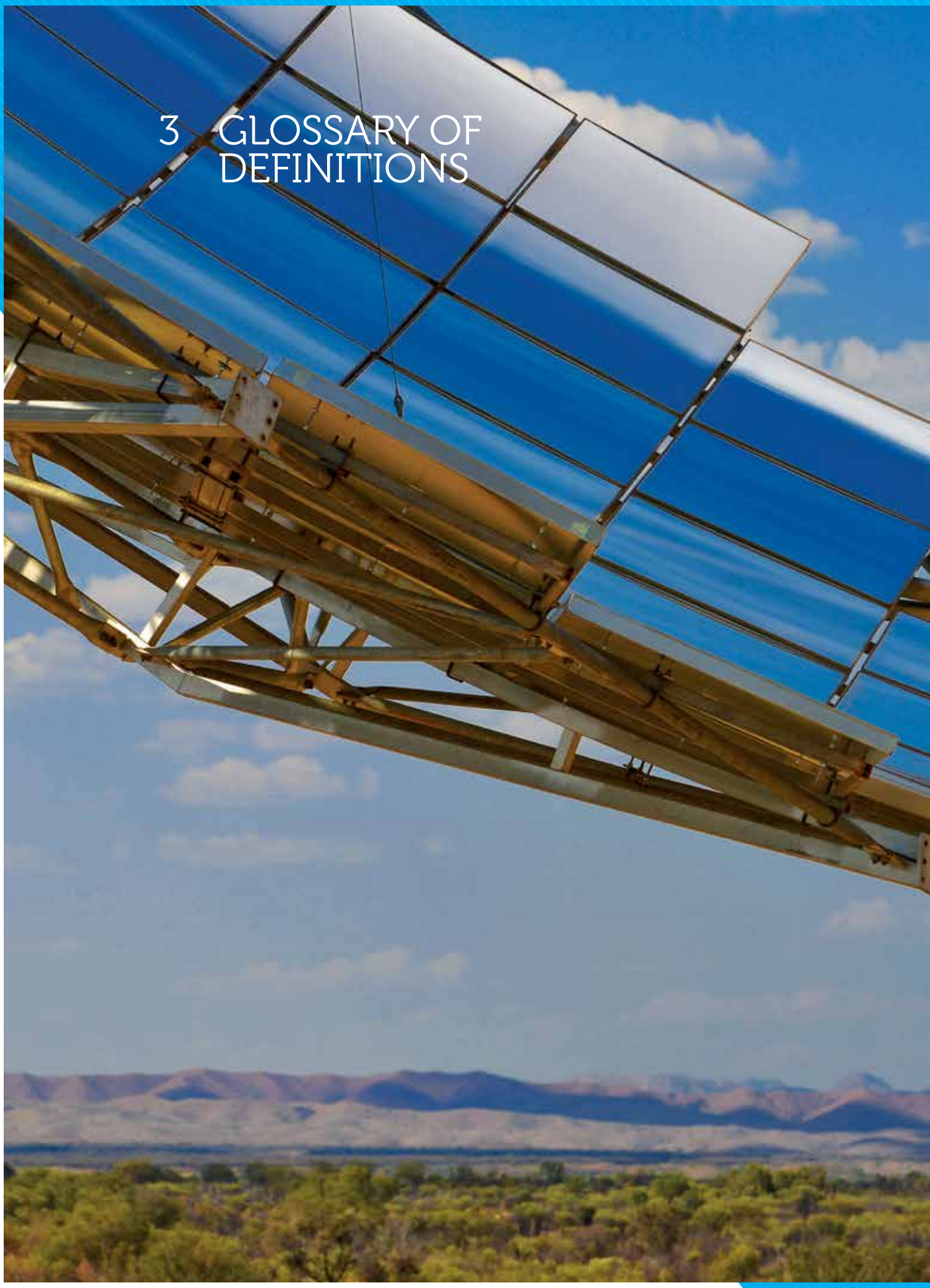
3 GLOSSARY OF DEFINITIONS



Agreed Service Levels: PWC has responsibility for the provision of reliable essential services (power, water and wastewater) to 72 remote Indigenous communities across the NT. The minimum service levels to be provided by PWC are based on the service outcomes that would be expected in other similar sized and located communities in the NT. PWC reports to the NTG on performance against these minimum service levels however they are not regulated by the NT Utilities Commission.

Community Service Obligation (CSO): In the Handbook, the term CSO refers to the payment the NTG provides to PWC in order to fund the shortfall between the cost to supply electricity in remote Indigenous communities and the revenue recovered from customers. Due to the increasing cost of providing electricity services to remote communities (associated with increasing diesel fuel cost, increasing electricity demand, increasing supply quality expectations and aging infrastructure), the shortfall gap (and hence the required CSO) is also increasing.

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.

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.

Minimum loading: Refers to the minimum recommended load factor (per cent) 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 per cent 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.

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.

Penetration: Solar penetration in hybrid mini-grid systems is typically classified by two numbers: energy penetration and power penetration. Energy penetration (average penetration, [kWh/kWh]) is the fraction of total energy solar provides to the system, usually assessed on a per annum basis. Power penetration (instantaneous penetration, [kW/kW]) is the fraction of power solar provides instantaneously to the power system. For example, a solar system may reach 80 per cent instantaneous power penetration at times and provide 30 per cent annual energy penetration overall.

Power Purchase Agreement (PPA): Refers to a contract between two separate entities regarding the supply and purchase of electricity. PWC utilises PPA contracts with independent third parties for the supply of electricity to six remote Indigenous communities. Under these PPA models, PWC procures only kWh units from the third party. This means, crucially, that PWC 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 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), PWC is responsible for the provision of reliable power overall. This means that PWC 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, PWC 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 in remote communities serviced by PWC. PWC operates over 50 mini-grid power stations, the majority of which rely solely on diesel fuel for power generation. These power stations vary in size from 300kW up to 5MW.

Quality of supply: PWC is contracted to provide reliable, safe, utility-grade power with a minimum level of service that equals the service outcomes that would be expected in other similar sized and located communities in the NT. PWC reports to the NTG on performance against agreed minimum service levels, however remote community grids are not regulated by the NT Utilities Commission.

Remote Indigenous Communities: Refers to the 72 nominated remote Indigenous communities that PWC (via its not-for-profit subsidiary IES) is responsible for providing essential services (power, water, wastewater) to, on behalf of the NTG. 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.

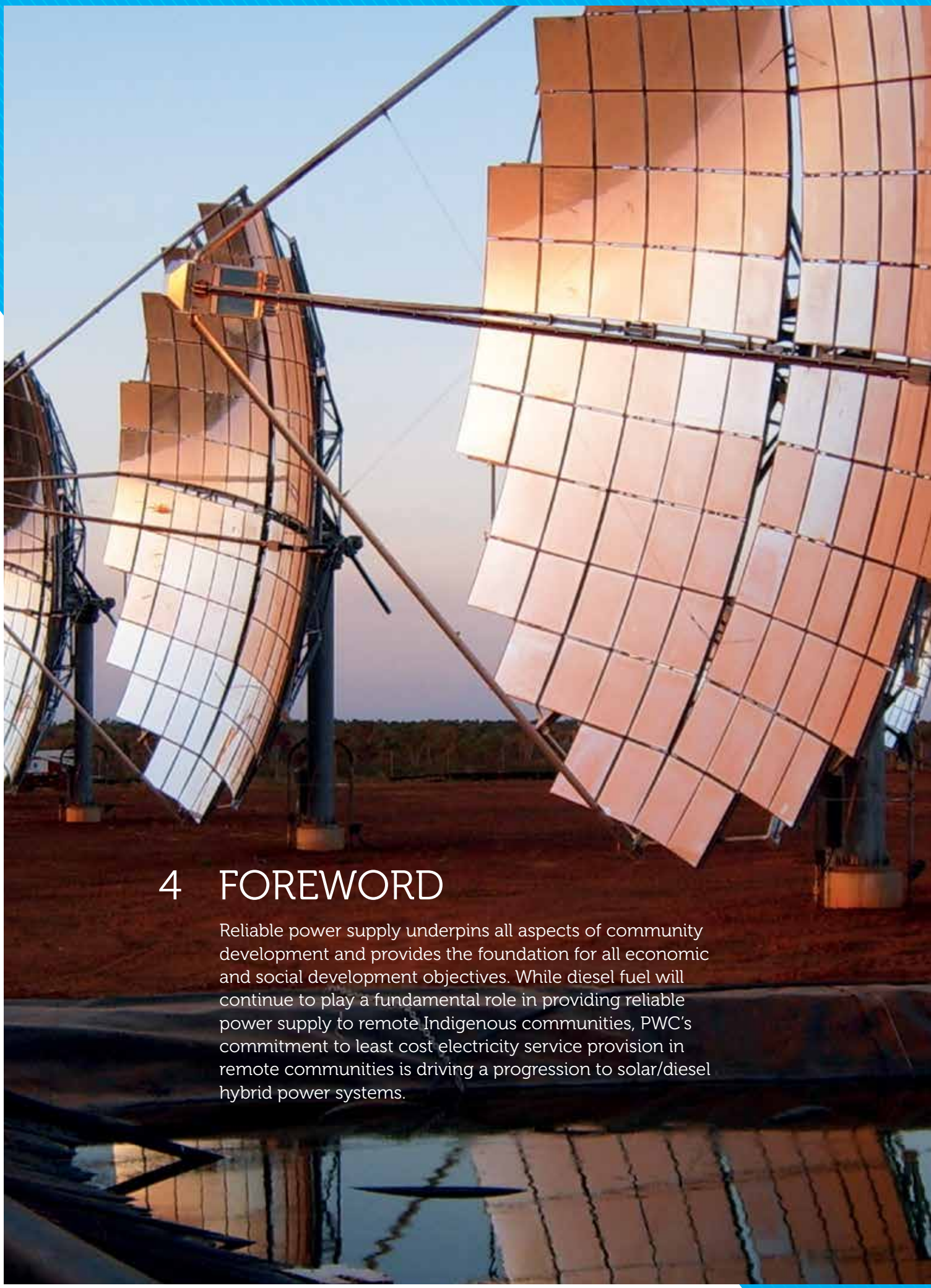
Solar: In the Handbook the term 'solar' refers to solar photovoltaic (PV) technology, not solar thermal technology.

Solar/Diesel mini-grid: In the Handbook the term solar/diesel mini-grid describes a hybrid mini-grid power system using solar and diesel generation operating in a remote Indigenous community serviced by PWC in the NT. 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 NT 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).

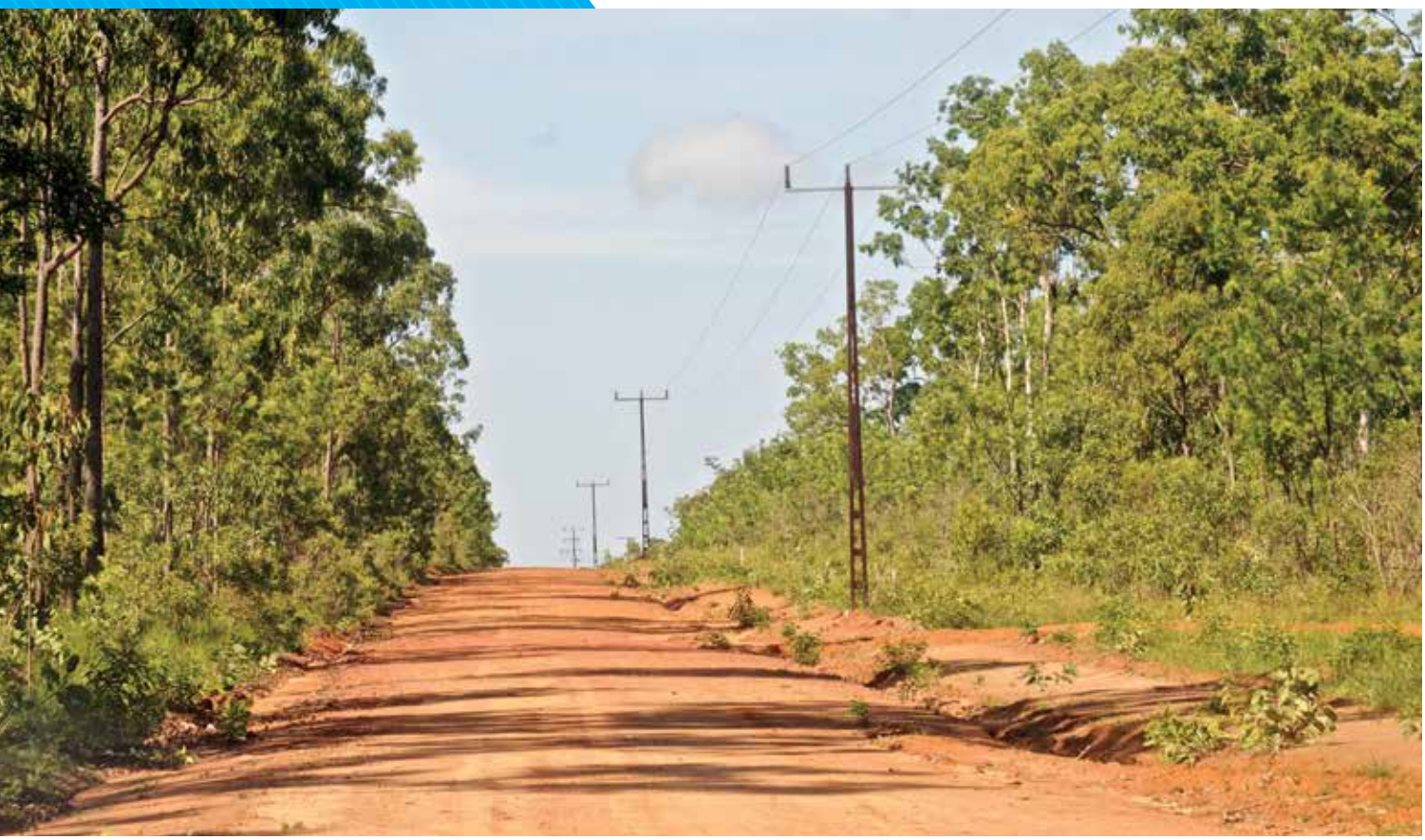
System cost: From a PWC perspective, system cost is based on the levelised cost of energy (LCOE), which means the lifetime cost electricity supply including construction, maintenance and fuel supply. System cost does not include 'sunk costs' such as the existing diesel generators and associated infrastructure.

Uniform tariff: The NTG operates a uniform tariff policy, which means that all (non-contestable) customers in the NT 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 NTG subsidises electricity for remote community customers via the CSO.



4 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 Indigenous communities, PWC's commitment to least cost electricity service provision in remote communities is driving a progression to solar/diesel hybrid power systems.



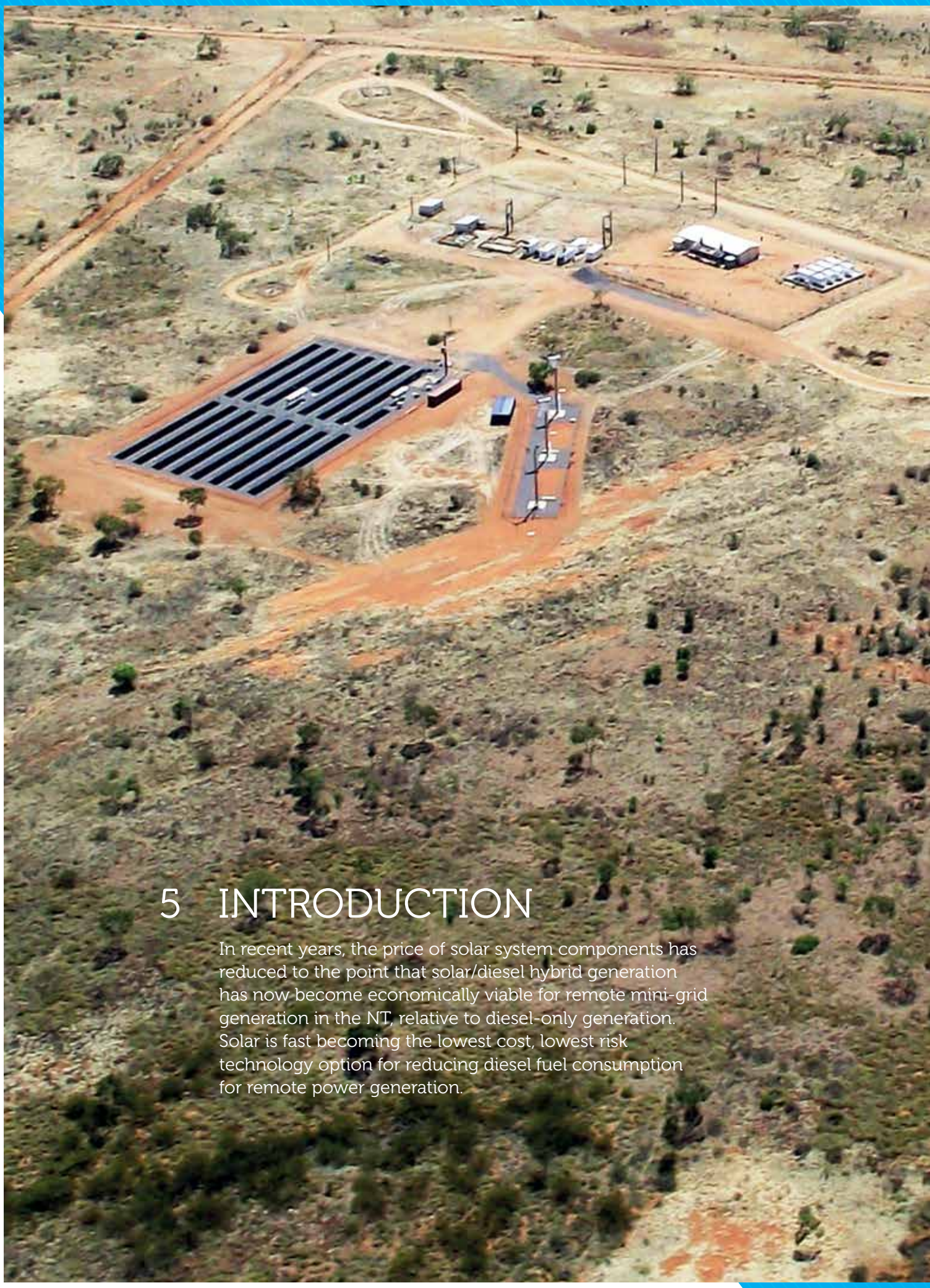
It is intended that the Handbook be updated in future as solar, diesel and storage technologies improve and our collective knowledge and experience designing, implementing, operating and maintaining solar/diesel hybrid mini-grid systems increases. This includes the addition of case studies of projects delivered under the ARENA Community and Regional Renewable Energy (CARRE) Program, providing information on technical system configuration, project outcomes and lessons learnt as a knowledge sharing tool.

It is also intended to further expand the Handbook scope to include other renewable energy technologies and energy efficiency practices being implemented in mini-grids across remote Australia; to capture the state of knowledge and experience in system design, implementation and operation and document specific current technical, regulatory, service standards, process and other requirements relating to off-grid energy service delivery and specify where these requirements differ across jurisdictions. Other key information which may be included in future revisions are occupational health and safety considerations, cultural awareness, material supply constraints, community engagement and consultation, and system acceptance testing.

Acknowledgments

Thanks are due to the following organisations who contributed to the development of the Handbook:

- Power and Water Corporation (Project Manager – Sara Johnston)
- Australian Renewable Energy Agency
- CAT Projects
- 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 components has reduced to the point that solar/diesel hybrid generation has now become economically viable for remote mini-grid generation in the NT, 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.

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. 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 PWC in the NT, servicing remote Indigenous communities on behalf of the Northern Territory Government (NTG). 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 the Daly River Solar Research Project and the TKLN Solar Project.

- Daly River Solar Research Project – a preliminary feasibility assessment of integrating solar into the existing diesel power station at Daly River.
- TKLN Solar Project – implementation of high penetration solar into three existing diesel mini-grids across the NT.

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 Indigenous 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).

The Handbook is focused on (2), specifically diesel mini-grids servicing remote Indigenous communities in the NT with generation capacity between 300 kilowatts (kW) – 5 megawatts (MW).

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-task11.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; 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 NT, PWC via 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 66 outstations across the NT. To achieve this, PWC 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. Of these mini-grid systems eight are solar/diesel hybrids, supplying electricity to eleven communities. These systems use a range of solar technologies, including concentrating photovoltaic (CPV) dishes and flat plate photovoltaic (PV) solar systems and have an installed capacity of over 1.7MW.

The key characteristics of PWC mini-grids are outlined below.

- **Diesel is the primary source of power generation:** this is the case even in the solar/diesel hybrid systems operating. This is a key distinction from 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. 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.
- **Full-automated control and SCADA:** remote power systems are managed on a continuous automated basis. In most instances the solar-diesel system interface occurs in the power station and the solar feeder is connected to the main switchboard, typically no loads are connected to the solar feeder between the solar system and the switchboard.

- **PWC-owned:** almost all mini-grid infrastructure and assets in major remote Indigenous communities is owned by PWC 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. PWC is responsible for providing generation, distribution and retail functions to remote community customers.
- **Quality of Supply:** PWC is contracted to provide reliable, safe, utility-grade power and meet service outcomes that would be expected in other communities of similar size and remoteness.
- Mini-grid **design and operation is demand-driven:** customer supply expectations are high and PWC must design and operate the power system in order to satisfy customer demand. This is distinct from mini-grids which are supply-driven whereby the design and operation are driven by the availability of the solar resource and the size and operating costs of the diesel generator(s) (i.e. the supply).
- PWC is licensed by the NT Utilities Commission to provide electricity to customers in remote Indigenous communities and regulated retail electricity **prices are set by the NTG**. The NTG 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 produce** electricity in remote Indigenous communities.
- The cost to supply electricity services is much higher than revenue recovered through tariffs. The NTG provides a subsidy to PWC 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 PWC is required to satisfy minimum service levels (acceptable voltage and frequency).
- PWC mini-grids are **isolated systems** i.e. they are not interconnected into larger networks. PWC has interconnected remote Indigenous communities into small regional mini-grid networks supplied by a single power station, where it has been economically efficient to do so.

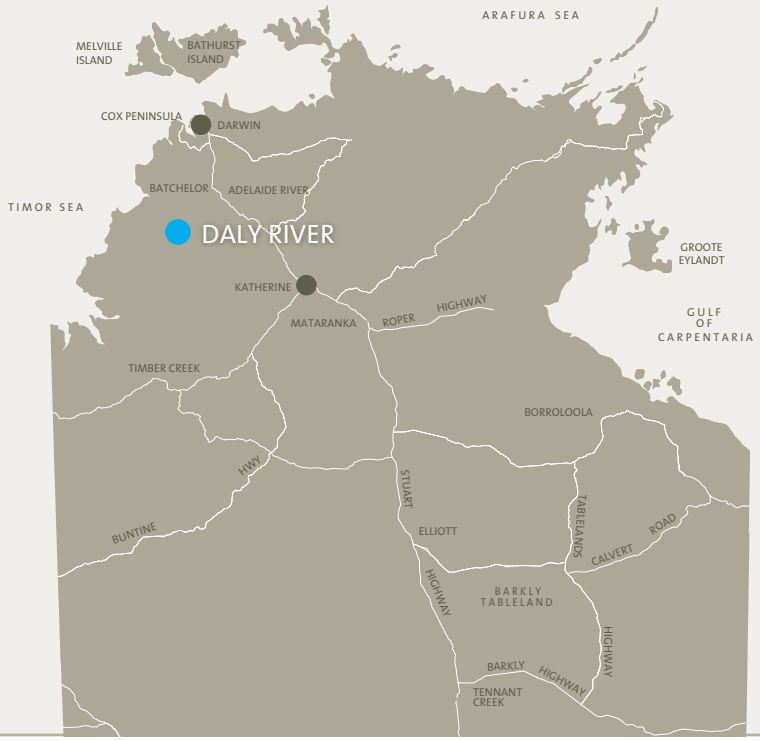
For more information regarding the operation of PWC's remote mini-grid power systems, refer to 6.2 PWC Diesel Mini-Grids. A map of the 72 remote Indigenous communities serviced by PWC is included in Appendix 9.1.

CASE STUDY: DALY RIVER COMMUNITY SOLAR/DIESEL PRELIMINARY FEASIBILITY ASSESSMENT

COMMUNITY OVERVIEW

Daly River (also known as Nauiyu Nambiyu) has a population of about 630[2] and is situated approximately 230 km south of Darwin on the banks of the Daly River. The Traditional Owners of the area are the Malak Malak people, who live both in Nauiyu Nambiyu and at Wooliana downstream from the community[3]. Town services available in Daly River include a local store, a health clinic, two primary schools and an air strip. Every year in May a sports carnival and art show with an evening concert attract up to 5 000 visitors. Renowned fishing competitions are held at Daly River that also attract many visitors to the community.

The annual electricity demand at Daly River is approximately 3 000MWh with a peak demand approximately 660kW. Daly River currently relies solely on diesel fuel for power generation however PWC is pursuing the development of a solar/diesel hybrid system.



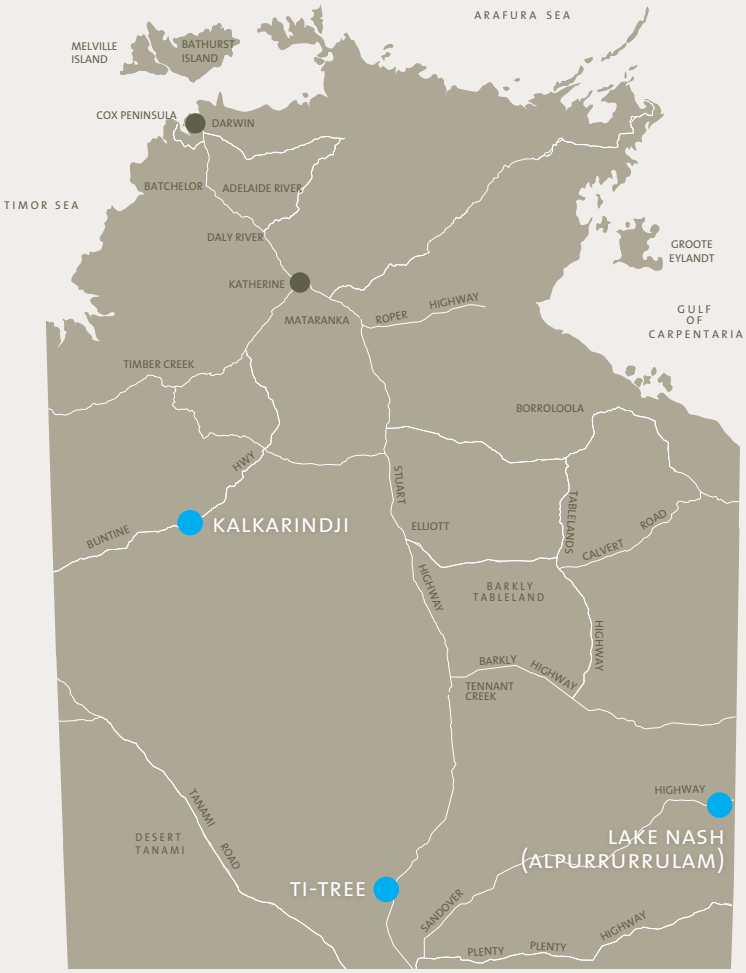
2 Source: www.bushtel.nt.gov.au accessed 09.09.13

3 Source: Victoria Daly Shire www.victoriadaly.nt.gov.au/service-centres/centre/nauiyu-daly-river accessed 14.05.13

CASE STUDY: TKLN SOLAR PROJECT

The TKLN Solar project involved the integration of high penetration solar systems at three remote NT communities (Ti-Tree, Kalkarindgi and Lake Nash (Alpurrurulam)), to the existing diesel power stations. The populations of these communities are approximately 170[4], 340[5], and 440[6] respectively.

TKLN Solar Project – map



4 Source: www.bushtel.nt.gov.au accessed 23.10.13

5 Source: Australian Bureau of Statistics Census 2011 accessed 23.10.13

6 Source: Australian Bureau of Statistics Census 2011 accessed 23.10.13

The primary project driver was to minimise diesel fuel consumption at the three communities and reduce the long term electricity generation costs. NTG provided $4 million to the project and the Australian Government provided $5 million to the project under the former Renewable Remote Power Generation Program (RRPGP).

Significant load growth had recently been observed and two of the three communities had in recent times 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 exceeds 1MWp, consisting of 992kW of solar (Kalkarindgi 402kW, Ti Tree 324kW, Alpurrurulam 266kW) and 45kW of wind turbines at Alpurrurulam.

The systems are designed with solar producing up to 85 per cent of power demand at a given instant which contributes up to 30 per cent of the average daily energy requirements of these communities. The large size of these systems and their high renewable energy contributions distinguishes them from other hybrid systems in Australia.

The TKLN Solar Project is included in the Handbook because:

- it is an example of the technical and financial viability of displacing significant volumes of diesel with high penetration solar using commercially available components (part-funded by government grants)
- it is based on a PPA contract model, with PWC 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). The development and operation of a solar system PPA in a mini-grid hybrid system has not been documented in detail before
- it is believed there is value in sharing knowledge and information on the TKLN Solar Project as solar/diesel hybrid mini-grids are expected to play a major role in future remote area electricity service delivery across Australia and in developing countries.

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.

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 NT 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.
- 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 per cent) 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.
- Quick installation – diesel engines are relatively easy to install.

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 significant risk exposure to fuel price increases. Diesel fuel is currently the single largest expense of PWC for remote community service provision, representing approximately a third of the entire PWC 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. PWC 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. All ESOs are required to have a minimum of a Certificate II qualification in Remote Area Essential Services within 12 months of the contract commencing. PWC, in partnership with a registered training provider have developed an accredited training program (Certificate I – IV) designed to provide ESOs with a structured career path in remote area essential service provision.

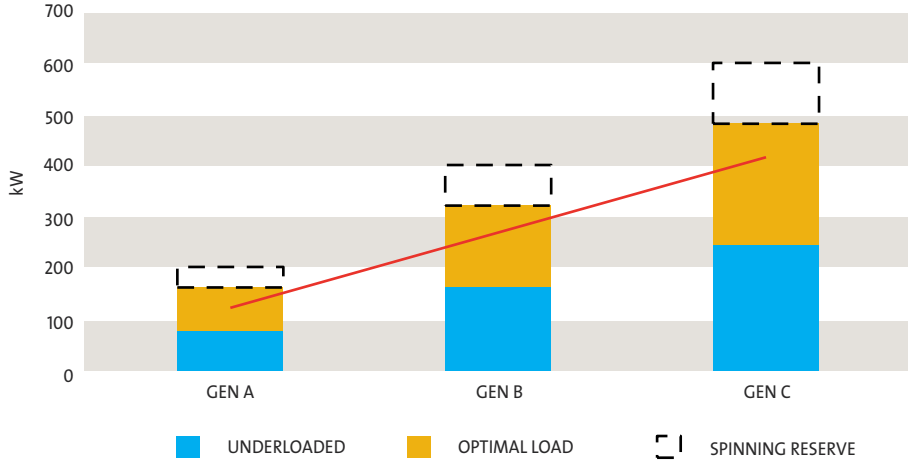
Two key diesel engine operational parameters are **minimum load factor** ('minimum loading') and **spinning reserve**. These parameters largely determine which generator is online. An engine load factor is the current output of the generator divided by its rated capacity. Most engine manufacturers recommend not operating engines for prolonged periods below 40 per cent 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 per cent 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 PWC 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.

6.2 PWC DIESEL MINI-GRIDS

Diesel engine sizing

PWC utilises multiple generator sets of different sizes at each mini-grid power station to best match load (avoid generator underloading) and to provide redundancy to ensure continuous supply. This is a deliberate design decision in order to service the wide load range that is common in remote Indigenous 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 NT can vary between 3:1 to 5:1 (primarily due to high cooling loads in summer/wet season).

Typical PWC Mini-Grid Generator Sizing



Configuration characteristics:

- three or four generators with ascending power ratings
- the 70 per cent load point of a small engine ideally corresponds to the 40 per cent load point of the medium engine
- the small size plus medium engine size is usually 125 per cent of the larger engine size, providing (N-1) redundancy in the event that the largest engine fails
- generators nominally rated to operate between 60 per cent and 80 per cent of their prime power rating, delivering an average load factor of 70 per cent 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, as this configuration is associated with carrying much higher spinning reserve margins under normal operating conditions.

Diesel engine asset management

Under its Asset Management Plan, PWC manages an engine relocation and replacement program to ensure the generation plant at a community operates within its most efficient range. To manage capital costs and ensure the full asset life is achieved, the fleet of 175 engines is moved between communities as required to best match the load at each power station. This stems from the need to maximise the whole-of-life of generators that become too small to operate in power stations where growth for power demand outpaces the nominal life cycle. In 2012, approximately 12 engines were relocated. Engine life is approximately 50 000 hours (around 12 years). This generator rotational policy is complementary to the wide-scale rollout of solar into existing diesel mini-grids across the NT, as generators may be moved around to achieve the best combination of solar and diesel engine size to match the community demand (to achieve highest possible overall power station efficiency and lowest marginal cost of production). When new generation plant is required, PWC procures engines that incorporate current high efficiency technology that meets international emissions standards.

PWC has standardised all remote power stations by manufacturer to achieve efficiencies in serving consumables, holding stock of spares and operator training and support.

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 NT.

7.1 BENEFITS

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

- solar reduces the kWh that must be generated using diesel fuel, resulting in diesel savings. Note that in PWC grids, solar 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. A high reliance on diesel fuel for remote power generation therefore represents considerable and increasing financial risk to PWC and the NTG. PWC 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 NT 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.

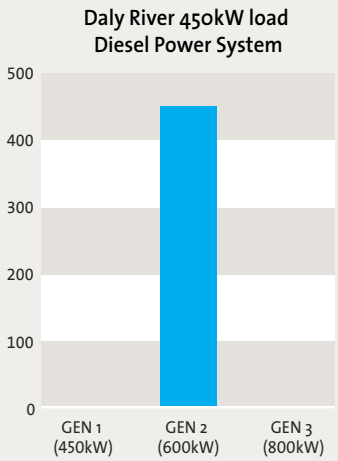
Generating power from solar energy instead of diesel fuel also results in reduced greenhouse gas emissions. Furthermore solar systems create renewable energy certificates which can be traded under the Australian Government's Renewable Energy Target. Revenue raised from renewable energy certificates enhances the value proposition of incorporating solar into an existing diesel mini-grid.

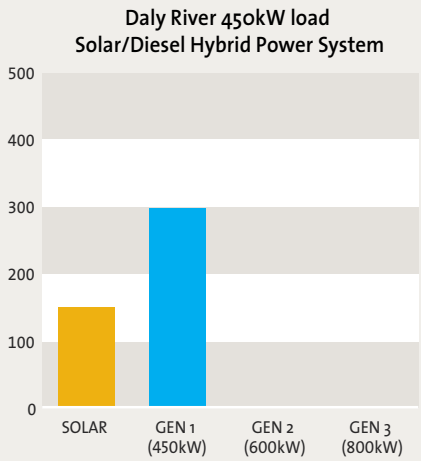
Incorporating solar into a diesel mini-grid can mean that a smaller diesel generator (operating in parallel with solar) services the load. This can result in reduced runtime hours on larger generators, potentially resulting in reduced operational and maintenance costs.

CASE STUDY: SOLAR/DIESEL PRELIMINARY FEASIBILITY ASSESSMENT DALY RIVER

Daly River power station is made up of three diesel generators with capacities of 450kW, 600kW and 800kW. The charts below illustrate how incorporating solar at Daly River may alter the size of the generator that would be required online to service a 450kW load.

Note that if the solar/diesel system design results in changing the generator that is online servicing the load (in parallel with solar), energy storage may be required to ensure overall system stability and reliability during cloud events.





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 cost ($/kWh)).

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

7.2.1 QUALITY OF SUPPLY REQUIREMENTS

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

Nominal voltages:	**High Voltage (HV)** **Low Voltage (LV)**	**11kV, 22kV** **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 to significantly differ 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. Dropping a large load on a generator in a short timeframe can drag 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). 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.

It is also important to note that when solar is implemented into a PWC diesel mini-grid, the objective is to displace diesel fuel not 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.

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 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

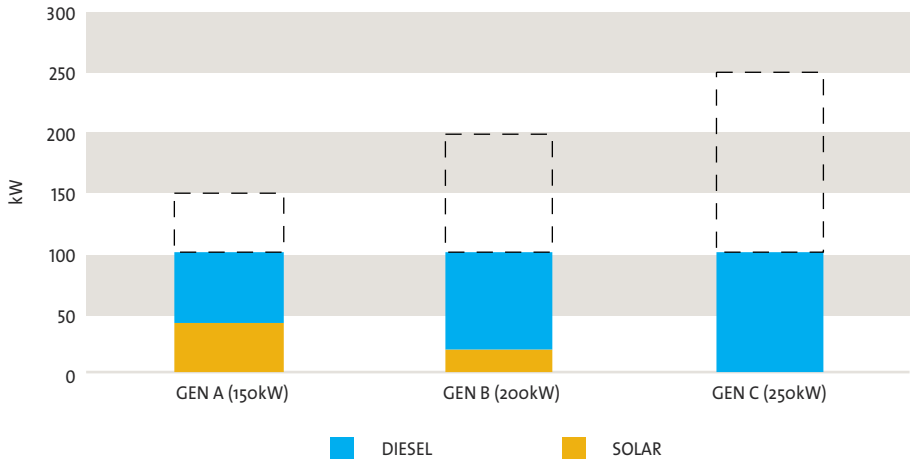
The capacities of the existing diesel generators will limit the solar penetration level achievable. The primary constraint is diesel engine minimum loading. As mentioned, diesel engines can be damaged by extended operation at low loads and to avoid this, the minimum loading of diesel engines is typically between 40 and 60 per cent (of nameplate power rating). This varies depending on engine characteristics such as age, manufacturer, RPM and governor (electronic or mechanical).

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 generators 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 per cent 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) – for illustration

Generator	Rated Capacity	Minimum Loading (40 per cent load factor)	Net load 'available' to be serviced by solar	Resultant solar power penetration (instantaneous)
A	150kW	60kW	40kW (100kW – 60kW)	40%
B	200kW	80kW	20kW (100kW – 80kW)	20%
C	250kW	100kW	0kW (100kW – 100kW)	0%

Impact of diesel engine size on penetration – illustration



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 two 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.

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 respected.

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 penetration 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 feeder, requiring an expensive upgrade of the entire board.

Distributed generation

The existence of distributed generation (such as customer-owned rooftop solar) is also a key consideration, as remote Indigenous 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. This is unlike the case in larger grids such as Alice Springs, where recent ARENA-funded research undertaken by CAT Projects suggests that the geographical diversity of distributed solar generation reduces the 'net variability' of their output.

In existing diesel mini-grid systems, a key determinant of the 'maximum allowable size' of customer-owned solar is the spinning reserve setpoint of the diesel generators. The extent to which the spinning reserve margin is already 'fully exhausted' by distributed generation is therefore a consideration for the development of solar/diesel hybrid systems; particularly low penetration systems which incorporate no 'smoothing' mechanism such as energy storage.

7.2.3 REMOTENESS

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

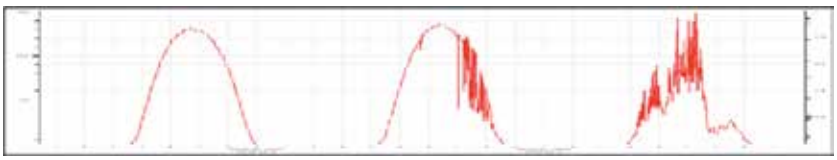
There is often limited on-site technical support available for maintenance work on remote power stations and as such there is an additional cost associated with mobilising staff and/or contractors to conduct this work. This should be a consideration for solar/diesel hybrid system development as different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

7.2.4 INTERMITTENCY

The integration of solar power into diesel mini-grids can be challenging; largely due to the intermittency 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 system output intermittency experienced at one of the TKLN Solar Project sites.

Illustrating solar intermittency (PWC 2013)



Generally, diesel engines are capable of this ramp rate (i.e. the rate of change is within its step-load capabilities), however if the overall load is greater than the engine's capacity the overall power system stability is jeopardised.

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 real 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). LCOE excludes the sunk cost of existing infrastructure, such as the existing diesel generators and power station infrastructure.

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 PWC 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.

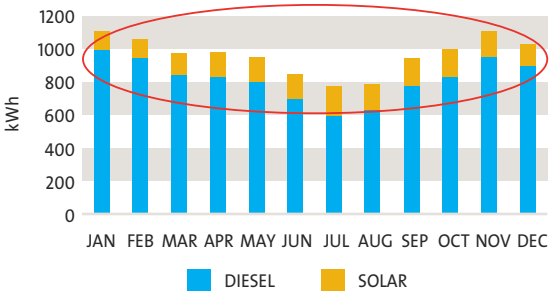
7.3 DESIGN CONSIDERATIONS

As mentioned, the key constraints which influence solar/diesel hybrid system design decisions in the NT 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.

7.3.1 SOLAR PENETRATION AND CONTROL

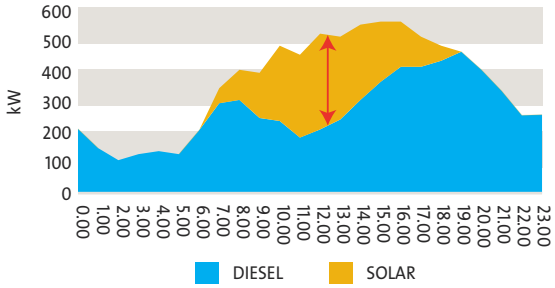
Solar penetration is typically classified by two numbers: energy penetration and power penetration. Energy penetration (average penetration, [kWh/kWh]) is the fraction of total energy solar provides to the system, which is generally assessed over a fixed period (commonly per year). Power penetration (instantaneous penetration, [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 per cent annual energy penetration and 60 per cent instantaneous power penetration.

15% Annual Energy Penetration (kWh)



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

60% Instantaneous Power Penetration (kW)



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

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

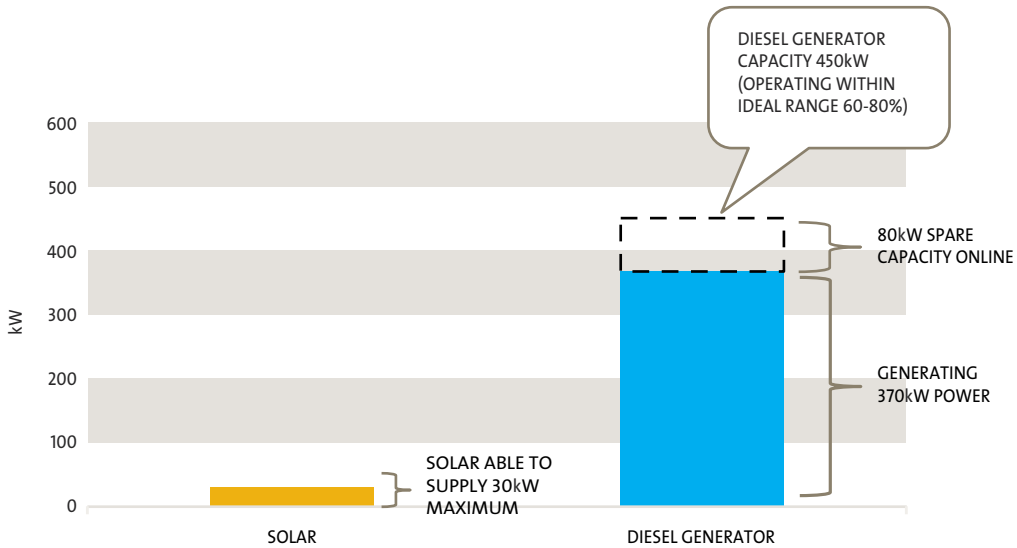
Outlined below is a low, medium and high penetration solar/diesel hybrid system however it is important to note that these terms are not universally defined.

Low penetration

In a low penetration solar/diesel hybrid system, solar capacity is limited to the static spinning reserve margin of the power system (typically between 30 and 80kW). Low penetration 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 diesel generator would 'pick up' the additional load within its available spinning reserve).

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

Example Low Penetration System: 400kW load without integration



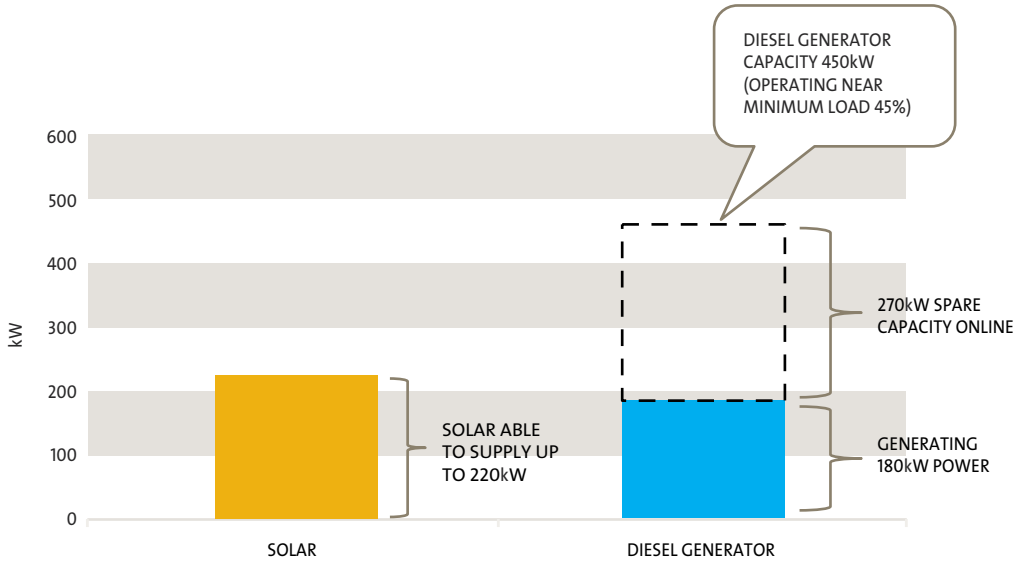
Note: this chart depicts a single point in time
SOLAR ENERGY IS LIMITED TO POWER STATION SPINNING RESERVE PARAMETER

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. Customer-owned solar systems in remote communities essentially operate as low penetration systems.

Medium penetration

In a medium penetration solar/diesel hybrid system, 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. In determining this value, 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 per cent 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. It has been estimated that diesel fuel savings up to 20 per cent per annum can be achieved with medium penetration system configurations.

Example Medium Penetration System: 400kW load with integration



SOLAR ENERGY CAN PROVIDE MORE THAN 7 TIMES MORE THAN THE 'WITHOUT INTEGRATION' CASE

Note: this chart depicts a single point in time

High penetration

In a high penetration solar/diesel system energy storage is required 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 penetration solar/diesel hybrid systems to work efficiently full integration is required between the solar and diesel control systems.

CASE STUDY: TKLN SOLAR PROJECT – EXAMPLE HIGH PENETRATION SYSTEM

The TKLN Solar Project incorporates an energy storage system to supplement solar output. Epuron coined this system the Grid Stability System (GSS). When a cloud event occurs, the GSS supplements the solar output. The contribution of the GSS reduces the effective rate of solar output change. This behaviour has been designed to allow the diesel generator enough time to adjust to the increasing load and the control system to start a larger generator if necessary. The PPA penalty scheme is designed to ensure an acceptable rate of change is maintained. Failure to do so risks power station stability and incurs a financial penalty.

SOLAR CONTROL METHOD

As a high penetration system design, the ability to regulate or dump excess solar output is required to ensure system stability. The choice of regulation method and its dynamic behaviour will affect economic and technical performance. Through experience under the TKLN Solar Project, a method to manage these behaviours has been developed. This experience is outlined below.

A SMA Power Reducer device was incorporated into system design capable of regulating solar inverter output in the range 0 – 100 per cent defined by 16 steps. For the ~400kW solar array at Kalkarindgi each Power Reducer step corresponded to 25kW. Step size has implications. Ideally the solar array could be controlled to the single kW tolerance. The setpoint calculated by the diesel power station is rounded to the single kW. The GSS is unable to match the setpoint unless it coincides with one of the step sizes, e.g. 25kW at Kalkarindgi. The GSS was initially designed to select the nearest Power Reducer step equal or below the setpoint value. The decision not to ever exceed the setpoint value was intended to avoid underloading of the diesel generator. For example if the setpoint value was 349kW, the GSS would select power reduced step 12 (325kW) rather than 13 (350kW) which would exceed the setpoint by 1kW. In this example 24kW of solar output would be forgone to avoid a 1kW underloading of the diesel generator. On average this approach would under deliver at a rate of approximately 12kW (half a power reducer step size) relative to the setpoint. It was recognised that over the life of the project this curtailment of solar energy contribution would be significant.

The Power Reducer system is not designed for rapid setpoint control. It takes approximately 20 seconds for a new Power Reducer value (step) to be conveyed to all string inverters. This response latency required some complex control code development inside the GSS to manage and provide dynamic control. Furthermore the GSS responds to every setpoint value. If a modest 5kW load in the community is switched off and back on within a few seconds, the setpoint would suddenly decrease 5kW then increase 5kW. This swing might be sufficient to cause the GSS to decrement one power reducer step, which would take another 20 seconds to respond. By examination of early system performance data it was noted that many 'unnecessary' power reducer steps were occurring as the GSS tried to follow the setpoint. On one hand sensitive setpoint following was needed so rapid response to events like feeder trips would occur, however the cost for this responsiveness was that there were many Power Reducer changes that did not enhance performance but instead caused the solar output to be reduced unnecessarily.

To address this the setpoint calculation rounds the setpoint value to the best fit power reducer step value (e.g. at Kalkarindgi 25, 50, 75kW) and the setpoint value remains stable for one minute unless a disruptive event occurs, such as a feeder shed. This avoids unnecessary step changes. If a feeder shed occurs the system reverts to a simple difference calculation so the GSS can respond dynamically to this event. The performance of these changes was modelled and validated using real system data prior to implementation.

Note that since the TKLN systems were designed, refined methods for controlling string inverters have been developed. New communication schemes allow sub-second communication to inverters and linear control (versus stepped control).

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. While one minute or one hour solar resource data is sufficient to estimate system performance and economics at a high level; smaller interval solar data (<= 1 second) is required in order to appropriately design a hybrid system, mitigate system performance risk and make an informed investment decision. This is because 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.

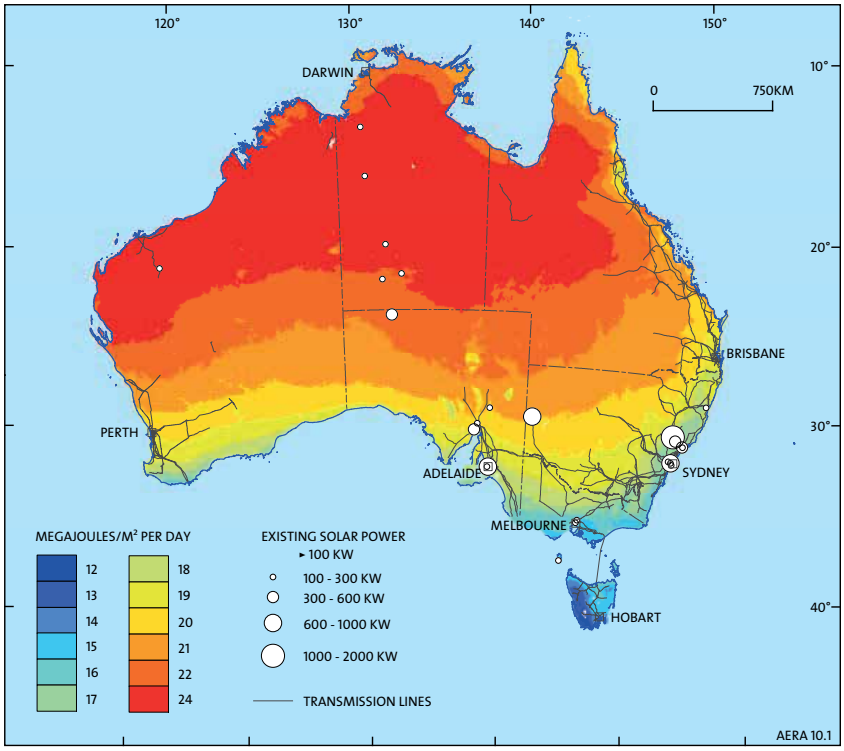
SOLAR RESOURCE DATA

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 NT (and indeed most of Australia) has very good solar resource. As shown in the figure below, most of the NT receives on average up to 24MJ/m^2 per day.

BOM Solar Resource Data (2009)

Annual Average Solar Radiation



The Top End of the NT 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 NT (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 the seasonal variation is not as great as in the Top End.

CASE STUDY: TKLN SOLAR PROJECT – SOLAR RESOURCE ASSESSMENT

As highlighted, the characteristics of solar resource variation (rate of change and scale of change) influence the design of the output 'smoothing' equipment; in the case of TKLN this relates to the size of the battery inverters.

There was a lack of site specific solar resource reference data to use during the design stage of the TKLN solar systems and the technical review of the proposed design. As a consequence, while the tender documents specified solar output performance requirements (in terms of acceptable rate of change of solar system output during cloud events), they did not include data indicating how quickly the solar resource might vary during a cloud event. Reference data sets were sourced during the design process from a range of locations to inform the system design decisions. The only publicly available one second solar system output dataset was from a test site in Hawaii, which indicated that within a one minute interval the worst case output variation was 40 per cent. The design of the TKLN 'smoothing system' was based on this variation, with the inclusion of a safety margin; specifically it was designed to exceed 40 per cent of array nominal peak output.

Since the commissioning of the TKLN sites, solar output variability data has become available and is showing that clouds can reduce solar output by up to 80 per cent in six seconds. Both the magnitude and the rate of solar output reduction experienced at the TKLN sites are much greater than those experienced at the Hawaii test site. This is in part due to difference in system array size, the Hawaii system is 1.5MWp, i.e. five to six times larger than the TKLN solar systems. This is consistent with research which shows that as solar system array sizes increase there is an averaging or low pass filter effect that reduces the magnitude and rate of change i.e. solar output variability is inversely proportional to array size. This is similar to the filter effect that is achieved by geographically dispersing solar systems. CAT Projects is currently undertaking research to analyse variations in instantaneous weather effects across Alice Springs and quantifying the extent to which the effects of intermittency can be reduced in this way. This research is ARENA funded; preliminary results can be found in Appendix 9.3.

Experience at Kalkarindgi has shown that in peak summer conditions when solar output is at its maximum, large highly opaque clouds can reduce the solar output beyond the capacity of the 'smoothing' system. During the TKLN testing and commissioning phase, cloud events such as this resulted in a station black start. In order to address the magnitude of solar variability and avoid future black start events, the Kalkarindgi system maximum solar output has been partially limited. This risk mitigation strategy is expected to result in less than 0.5 per cent yield loss.

The PPA document was structured to consider one minute intervals for calculation of rates of change and penalty calculations. As a consequence the GSS control loops were not optimised for fast responses. Early field experience showed that there was latency between the initial reduction of solar output and the response of the GSS. This meant that in certain operating conditions the delayed GSS response could result in generator overload before GSS support was received. The GSS performance was improved to respond quickly to solar output changes.

Understanding the solar resource variability at the TKLN sites and including site relevant solar variability information into the tender would have enabled the GSS design to support solar output variations.

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 NT.

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 size

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.

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 PWC 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 NT. 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.

Concentrating solar photovoltaics

Concentrating solar photovoltaics (CPV) technologies are currently utilised in three remote Indigenous communities serviced by PWC. CPV technology requires direct beam radiation and so is well-suited to the arid climate in Central Australia where cloud cover is minimal. That said, CPV technologies require tracking arrays, and as noted above the additional solar power that can be harnessed by the CPV technology must be considered in light of the increased O&M associated with the more complex system, which is costly in remote areas. Furthermore the reliance of CPV technology on beam radiation may also substantially increase the impact of intermittent cloud cover on system output.

DALY RIVER: SOLAR/DIESEL PRELIMINARY FEASIBILITY ASSESSMENT

TECHNOLOGY ASSESSMENT

A solar feasibility assessment for Daly River was undertaken in which a comparison was made between three types of panel technologies and between fixed or tracking arrays.

PVsyst modelling software (www.pvsyst.com) was used to compare module technologies and array tilts to determine which combination provided the most 'usable' solar energy. The results indicated that the cadmium telluride modules achieved the highest output, however due to the toxicity associated with cadmium telluride, monocrystalline arrays were deemed to be the preferred option.

The remoteness of Daly River contributed to the choice of fixed arrays over tracking arrays, due to the costs associated with mobilising technician personnel to undertake repairs and maintenance.

PVsyst modelling results indicate that a 10 degree array tilt produces the most usable solar power output over a year, on average, in the context of the Daly River annual load profile. Array tilts of 10, 15, 20 and 25 degrees were considered.

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 are not in widespread use, they are under active commercial development and they may find widespread use in the future. These technologies are outlined below.

Low load diesel engines

As mentioned, most diesel engine manufacturers for stationary applications recommend a minimum loading to avoid contravening warranty conditions. 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, this 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.

That said, there are degrees of 'low load' and successful operational experience outside of manufacturers' recommended minimum load ratings has been reported. A small number of remote power system operators in Australia have used diesel engines at low load in wind/diesel and solar/diesel systems. These operate down to very low loads (approximately 10 per cent) but operate at higher loads other times to 'undo' the effects of low load operation, using oil sampling to monitor for deleterious effects. Reportedly, operational experience to date (mostly with wind diesel systems) 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. 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.

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').

These functions are outlined in more detail below.

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 theoretically 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.

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. In addition, while cycle life for traditional energy storage (lead acid batteries) is assessed and reported based on given standards, it is not always clear that similar standards were adhered to by manufacturers of emerging energy storage systems. Furthermore the harsh operating conditions of the NT are such that the manufacturer's design life for the energy storage device is rarely 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 per cent 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. Much research and development has taken place in the energy storage sector over the past decades however, the market is not consolidated at the moment and many technologies offered have not been operated sufficiently long to be considered mature. Thus, 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 per cent.

7.3.5 LOAD CONTROL

LOAD MANAGEMENT

The term load management generally applies to the field of electricity service provision where the load is managed in order to optimise generator or network performance. There is a myriad of methods by which load management can be achieved, including supply-side and demand-side driven responses. For the purpose of the Handbook, the term load management is synonymous with load control, by which loads are directly controlled by the power station control system when required in order to manage grid stability during cloud events.

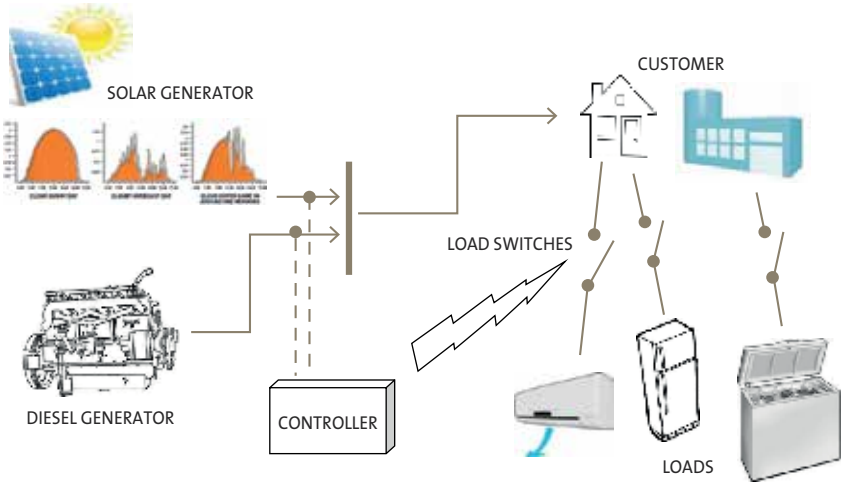
As discussed, a challenge with solar systems operating in mini-grids is that when a cloud passes over the panels causing shading, their power output can drop at a very high rate which can cause power system stability issues. Load management techniques such as load control may help mitigate this risk, by providing the power station control system the ability to instantaneously switch off loads temporarily if a cloud-event occurs or a rapid reduction in solar output is detected. Effectively being able to directly control loads increases the power system spinning reserve, as they can be taken offline instantaneously should solar power be lost (e.g. due to a cloud event). In terms of the power system, this results in the diesel generators not being required to suddenly 'pick-up' this additional load (that the solar system was no longer able to support), reducing the risk of power system instability. There is also the potential for load control to increase the amount of solar power that can be 'accepted' by the control system under normal operating conditions (i.e. not only during a cloud event), by effectively increasing the amount of spinning reserve available in the power station.

Essentially, this application of load management performs a similar role to that of energy storage in solar/diesel hybrid systems; it provides a buffer between solar output intermittency and the diesel generator response time.

ENERGY EFFICIENCY

PWC is actively involved in improving the efficiency of the operation of its infrastructure in remote communities. PWC is also committed to assisting customers to better understand energy and make informed decisions about managing their energy use. For more information go to: www.powerwater.com.au/sustainability_and_environment/save_on_power

Schematic: Possible configuration of a direct load control system



The schematic above illustrates a simplified diagram of how a direct load control system may work in a mini-grid. The solar and diesel generators feed information on their current operating parameters to the control system, while providing power to the grid. A network of individual controllable loads (typically appliances) in customers' premises are connected to power via switches. The switches in turn are connected via communications (hard-wired or radio) with the controller. When a cloud event occurs, the controller detects the ramp rate of the solar. If the overall load approaches the diesel generator's capacity and the online spinning reserve is insufficient to cover the full load, select loads are switched off. After a short time the controller would switch the select loads back on at a steady rate. A larger generator would be turned on to supply additional power if required. In this way, the solar contribution to the system can be increased without risking interruptions to the power supply during cloud events.

There is growing pressure from industry, utilities and energy conservation groups to standardise smart-grid technology. Australian Standard AS4755 is concerned with imposing standards on imported or Australian electrical goods so that they are capable of communicating with load management control hardware. The standard is targeted towards residential air-conditioners, water heaters and pool pumps and there is industry pressure to include electric vehicle chargers and other appliances.

In a load management network, a method of communication is required to transmit information from the central control location to the individual houses or buildings with the controllable loads. This communication needs to be at least one-way (from central control to the load) but ideally is bi-directional. In a bi-directional system information can be fed back to the central control location, such as the status of the load (on or off), the actual power consumption of the load (amps or kW) or even information about time scheduling of the load (for example air conditioners which are scheduled to turn off over night).

One aspect that is crucial to all of the communication technologies is the signal transmission is secure. This is secure from both a 'hacker' perspective and also from electrical noise and interference, so that it can be guaranteed that the desired communication is achieved. Often it is the various communication protocols that manage this task by way of signal encryption or check bits or similar.

Please see Appendix 9.6 Load Management – Technologies for further information.

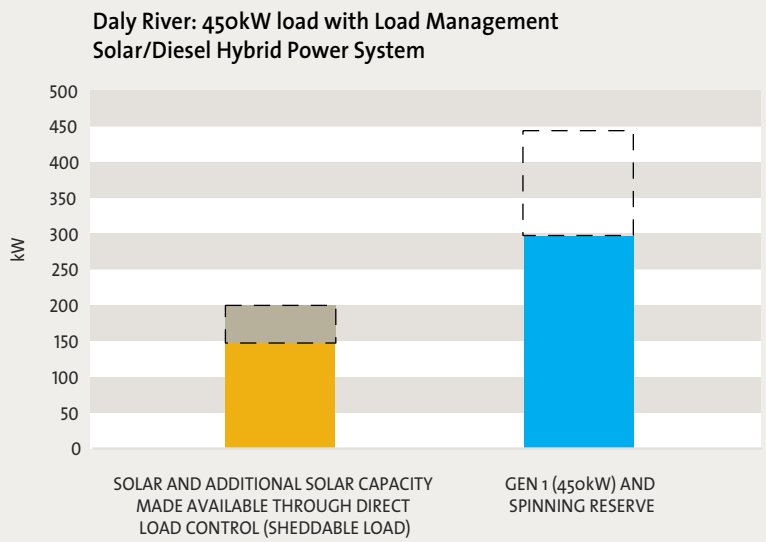
CASE STUDY: DALY RIVER – PRELIMINARY ASSESSMENT OF LOAD MANAGEMENT POTENTIAL

Due to increasing costs associated with remote essential service delivery, consideration of opportunities for efficiency gains and performance improvements via better load management is paramount. Therefore undertaking a load assessment is a critical component of solar/diesel hybrid system design. A preliminary investigation into the potential for load management to overcome the identified barriers to higher solar energy penetration in mini-grid systems and improve the overall efficiency of a solar/diesel hybrid power station has been undertaken, based on a case study of Daly River. The overarching objective of the preliminary investigation was to determine if load management (direct control and interruption) should be further pursued as way of optimising the performance of a hybrid solar/diesel power station at Daly River. Presented below is a summary of the results and key findings. Please see Appendix 9.5 Load management – Daly River for further details.

Study key findings and outcomes

- Preliminary results indicate there may be potential for up to 200kW available to be utilised for direct load control at Daly River to increase solar penetration and overall efficiency in a hybrid mini-grid system. These findings suggest there is scope for future investigation into load management opportunities at Daly River.
- Attempts to introduce load management must be done without negative impact to the price that customers pay for electricity or the quality and reliability of the electricity service provided.
- Prior to the commencement of a load management trial a comprehensive communications program is required to educate and inform customers. This should include the proposed duration and frequency of switch-off periods and incentives to participate.
- A generic load assessment model is a good starting point however considerable effort needs to be invested in customising the load management options to suit each specific community, in this case Daly River.
- Customers were generally supportive of the use of solar power to reduce diesel fuel consumption.
- Customers were generally interested in participating in a load management scheme, particularly if there was some incentive provided.
- Key appliances identified as suitable for load control included:
    - airconditioning units
    - air-handling or ventilation systems
    - stand-alone fridges and freezers
    - cool rooms
    - electric water heaters
    - irrigation water pumps and pool pumps

The chart below illustrates the potential increase in solar power contribution to a 450kW load at Daly River by the use of load control (brown shaded area).



NOTE: NOMINAL LOAD MANAGEMENT CAPACITY OF 25% OF SURVEYED POTENTIAL WHICH WAS 200kW

7.3.6 MODELLING TOOLS

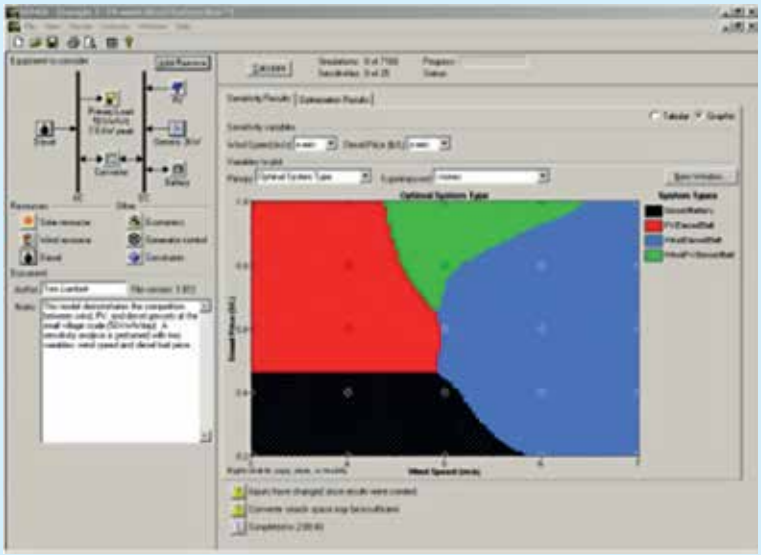
Simulation is an important aspect in the development of hybrid mini-grid systems, due to the complexity involved in the design of such systems. In 2011, IEA PVPS Task 11 undertook a survey to gain an understanding of the hybrid system modelling tools that were used internationally. Following this investigation,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

HOMER 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.



ASIM

To address a gap in available modelling tools, PWC recently developed ASIM (with ARENA support). ASIM is available to download via the PWC website (www.powerwater.com.au). 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 <5 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; 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 will be 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 PWC 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

ASIM AND HOMER: COMPLEMENTARY HYBRID MODELLING TOOLS FOR SOLAR/DIESEL FEASIBILITY ASSESSMENTS

ASIM and HOMER are complementary hybrid system analysis tools and PWC utilises both to conduct solar/diesel feasibility assessments and design comparisons. HOMER is a useful tool to undertake multiple optimisation and sensitivity analysis under a single simulation and determine the optimal system configuration and initial economic results given a set of high-level constraints (number and capacity of generators, solar system capacity etc). The HOMER-recommended configuration can then be modelled in ASIM, incorporating more specific input data (diesel fuel price escalation, generator call-up sequencing, load growth projections etc), to refine the cost estimate provided by HOMER and to assess how the system would work in detail (based on a one second analysis).

TMA – time series visualisation, analysis and reporting

TMA is used within the ASIM project in order to allow visualisation and manipulation (such as scaling or smoothing) of time series data. This is particularly valuable for larger data sets of irregularly sampled time values as used in ASIM. TMA is also capable of statistics and analysis functions including calculations over time (e.g. calculate the difference between the setpoint and the actual output over the year and display it) and can generate reasonable quality plots suitable for system analysis.

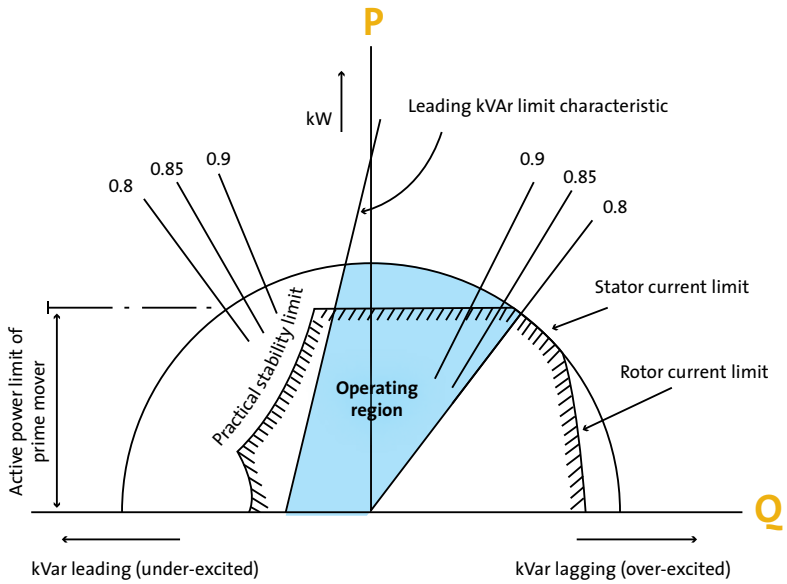
Other available tools for time series visualisation include Citect Process Analyst, MATLAB and OSIsoft PI Process Book. TMA differs from the above in that it is an open source project (GPL V3) and hence is suitable for use within ASIM for visualisation. Note that the ASIM framework itself does not require the use of TMA.

7.3.7 OTHER FACTORS

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 poor (<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.

Typical operating region of a generator



Ideally the solar generator and the diesel generator share VArs proportionally however PWC's experience has been that this level of solar inverter control is not provided by many vendors. 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.

In future, more vendors will offer the ability to control solar inverter power factor dynamically allowing inverters to contribute to VAr sharing.

Collaboration

In high technology projects where imperfect information exists, a collaborative approach is an effective way to hedge against uncertainties. As witnessed in the TKLN project, collaboration throughout the project's delivery built 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. The TKLN project benefited from constructive styles of engagement used at all stages.

8 CONCLUSION

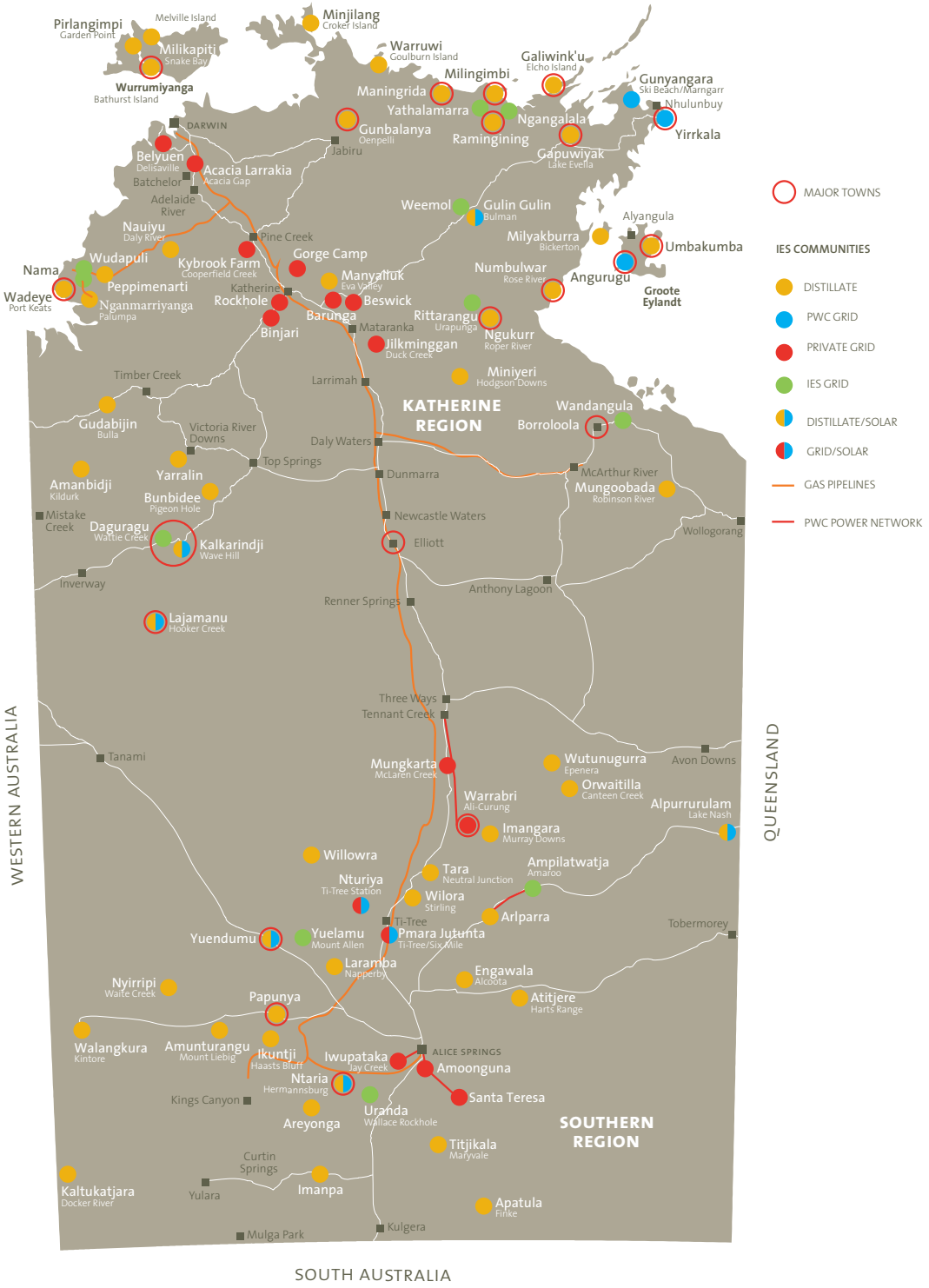
Despite being over 20 years since the first solar/diesel hybrid system was implemented in a remote NT community mini-grid, the total solar contribution in these mini-grids remains relatively small. To address this, PWC is pursuing a step-change in the remote power generation portfolio, through the hybridisation of the entire diesel mini-grid fleet. This has been made possible by the improving solar economics in recent years and the experience and knowledge PWC has gained through development, design and operation of the existing solar/diesel hybrid systems.

The Handbook is intended to inform the broader solar industry, academia and the general public about the remote community power supply context and the challenges associated with implementing solar into an existing diesel mini-grid to achieve fuel savings while maintaining a reliable, utility-grade electricity service. It is anticipated that future editions of the Handbook will be developed, by PWC and/or others, to further develop, strengthen and foster a knowledge sharing culture within the solar/diesel mini-grid industry in Australia and internationally, leading to more widespread applications of solar/diesel hybrid systems.

9 APPENDIX

9.1 REMOTE INDIGENOUS COMMUNITIES SERVICED BY PWC

Energy Source Map 2012



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 (kWp)	Technology
Ergon Energy	Doomadgee, Queensland	264	Flat plate, fixed array
Ergon Energy	Windorah, Queensland	130	Concentrating PV dishes, dual axis tracking
Horizon Power	Nullagine, Western Australia	200	Flat plate, single-axis tracking
Horizon Power	Marble Bar, Western Australia	300	Flat plate, single-axis tracking
Hydro Tasmania	King Island, Tasmania	100*	Flat plate, fixed array
Power and Water Corporation	Bulman, Northern Territory	56	Flat plate, fixed array
Power and Water Corporation	Kalkarindji, Northern Territory	402	Flat plate, fixed array
Power and Water Corporation	Kings Canyon, Northern Territory	225	Flat plate, fixed array
Power and Water Corporation	Lajamanu, Northern Territory	290	Concentrating PV dishes
Power and Water Corporation	Lake Nash (Alpurrurulam), Northern Territory	266*	Flat plate, fixed array
Power and Water Corporation	Ntaria (Hermannsburg), Northern Territory	192	Concentrating PV dishes, dual axis tracking
Power and Water Corporation	Ti Tree, Northern Territory	324	Flat plate, fixed array
Power and Water Corporation	Yuendumu, Northern Territory	240	Concentrating PV dishes, dual axis tracking

* These hybrid mini-grid systems also incorporate wind power

9.3 DISTRIBUTED GENERATION – ALICE SPRINGS INVESTIGATION

As part of an ARENA supported research project (*Analysis of variations in instantaneous weather effects*), nine weather stations were recently commissioned around Alice Springs to assist with research aimed at analysing variations in instantaneous weather effects across the geographical boundaries of an electricity grid. The weather stations were located in two rings of 5km and 15km radius, centred on the Desert Knowledge Australia Solar Centre (DKASC) demonstration facility.

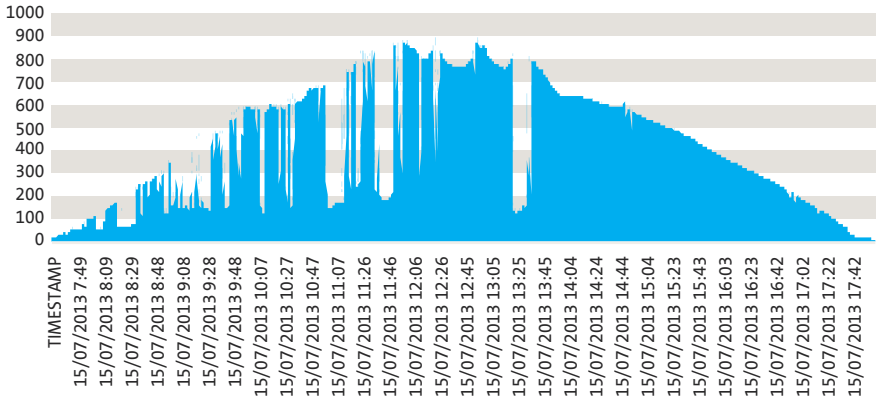
Preliminary findings from the first three months of insolation data gathered suggest that the effects of intermittency are greatly reduced by physically distributing solar generation around the grid and this in turn guarantees a greater availability of baseline solar generation.

The following graphs chart the insolation at six of the stations on a day of scattered cloud cover. Clearly shown are the variable insolation peaks and troughs at different times of the day for each site. The graph showing the combined insolation however indicates a baseline solar generation that could be guaranteed across the day.

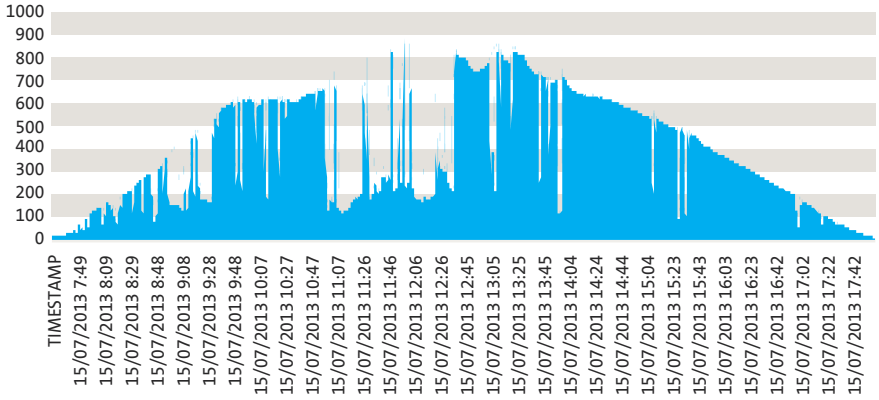
Insolation analysis – high variability – scattered cloud cover day – Date 15 July 2013

- Solar insolation across individual sites in Alice Springs Region

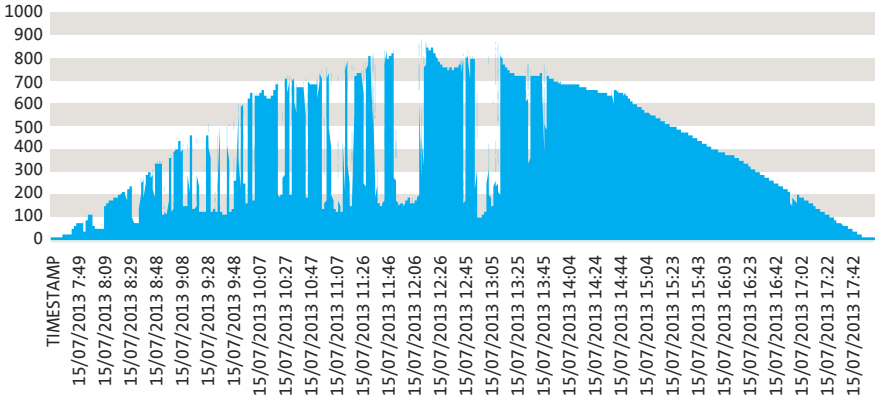
Nth Stuart Hwy



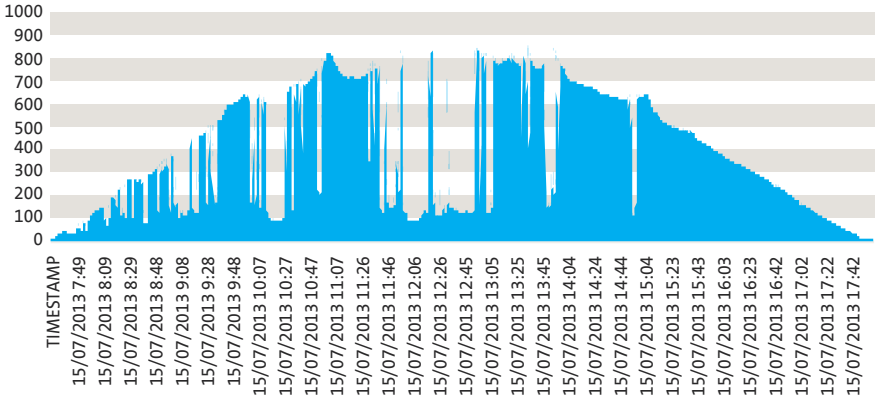
Stephens Rd



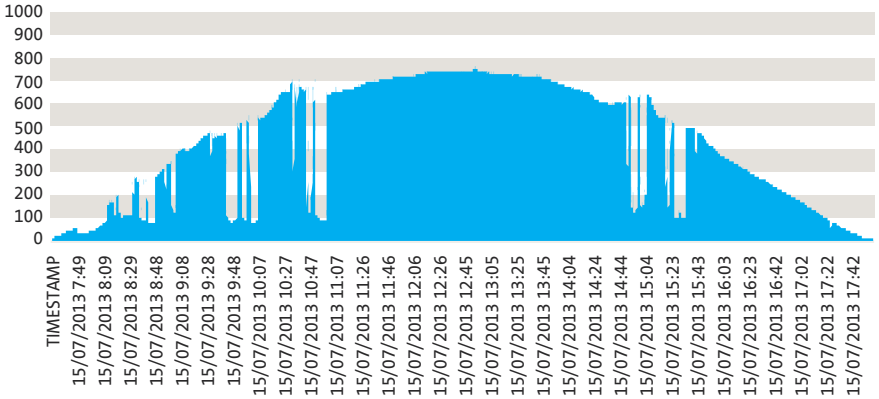
Ilparpa Rd



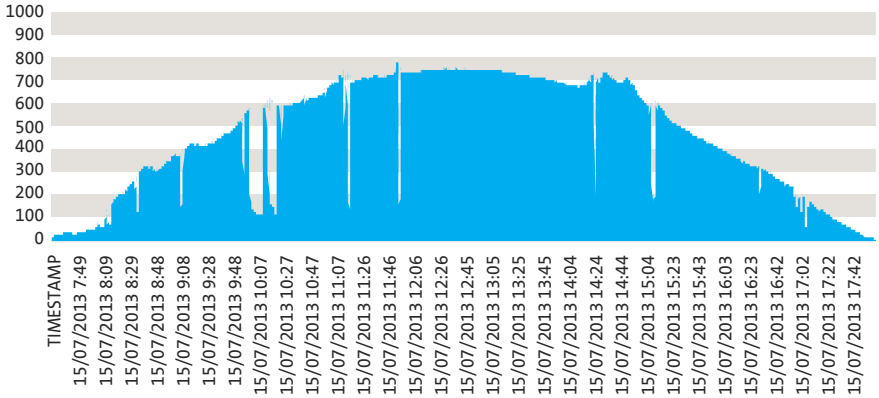
Ross Hwy



Deepwell Rd

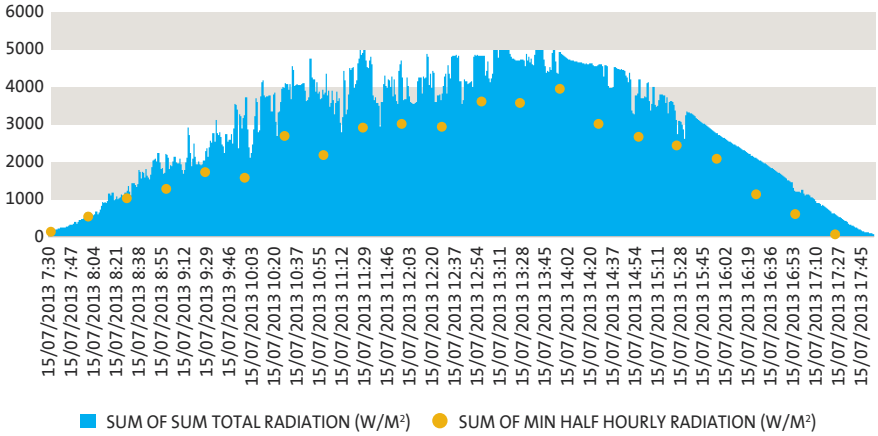


Brewer Rd



- Combined solar insolation across geographically dispersed sites in Alice Springs Region.

Sum global insolation of 7 sites with half hourly minimums



9.4 ENERGY STORAGE TECHNOLOGIES

Technologies used for ESS can be classified as electrochemical, electrothermal, electromechanical, and electromagnetic; and they can be rated by energy capacity and power capacity. The main technologies currently utilised are outlined below. While it is a rapidly changing field, this information provides a good starting point for investigations.

A multitude of **electrochemical ESS** are available, with many more under development. Lead acid batteries (flooded or valve regulated) and Nickel-Cadmium batteries can be considered the most mature technologies. However, even within these there are significant differences in type of manufacture based on intended application. This can significantly impact energy and power capacities and thus the suitability for intended use.

Other mature technologies are Lithium Ion and Lithium Polymer batteries, which can offer high energy and power densities at high energy density. However, their use in stationary applications is currently not attractive due to their high cost. Furthermore, several large-scale sodium-sulphite (NaS) battery installations exist.

Many new battery manufacturers are pushing into the market. Closest to maturity are several types of 'advanced lead acid' batteries which promise extended cycle life, higher energy density and increased power levels. Also potentially close to maturity are several types of flow battery. Various chemistries have been developed for this concept. It is hard to say which of these currently is the most likely to succeed.

Other technologies are under development, however some have not left the research lab, or where they have, need considerable more development before technical and economic viability is achieved.

Special cases of electrochemical storage are hydrogen fuel cells. The storage component of these systems is hydrogen tanks, which are cheap in initial investment, but exhibit high loss rates. Hydrogen gas can be generated by electrolysis and is then consumed in the fuel cell to generate power, however, electrolysers are rather inefficient (<20 – 50 per cent). The expected life of a fuel cell is generally not measured in cycles, but can be expected to be significantly less than 100 000 hours.

The three major **electromechanical ESS** are flywheels, compressed air energy storage (CAES) and pumped hydro power. Flywheels are generally employed in short-term storage power quality applications, while CAES and pumped hydro are more suitable for long-term energy storage.

Flywheels can be categorised into traditional steel rotor, low RPM flywheels and composite rotor, high RPM flywheels. Both technologies have been demonstrated and implemented in power quality applications. Due to their long cycle life, fast response and high power levels, flywheels are superior to electrochemical ESS in power quality applications. However, the cost for flywheels is significantly higher. Thus, a case by case comparison is required to determine if it is more economical to operate a flywheel ESS, or to accept the shorter life cycle of a cheaper ESS. In addition, many composite flywheels are still dealing with 'teething problems' due to advanced bearing and motor technologies.

CAES systems usually make use of the underground caverns of abandoned mines. At least two such systems have been in continuous operation since 1979, and 1991 respectively. The systems are used for load shifting of nuclear power plants and hence are in the order of 100s to 1 000s of MW. Recently smaller above-ground CAES systems have been proposed. However, none are in commercial operation.

Pumped Hydro ESS are the most cost effective large scale systems available to date. However, generally systems smaller than several MW are not considered. 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 local or regional geographical features.

Electromagnetic ESS are generally highly efficient, but very expensive. Both types of electromagnetic ESS, supercapacitors and superconducting magnetic energy storage (SMES), rely on highly specialised and costly materials. Due to this their application is generally limited to very small amounts of energy stored and thus they are only utilised in power quality applications.

Unlike the other ESS described above, most **electrothermal ESS** are not designed for an electricity-storage-electricity application, rather they make use of thermal energy requirements usually met by electricity or another form of energy. Electrothermal systems either store heat or cold to be released later either for direct use in heating or cooling applications, or to drive industrial processes. Electrothermal heaters employ bricks or water as the energy storage medium; electrothermal cooling systems use chilled water or ice. In this context ice is about 80 times more volume efficient, as the main contribution to meet a cooling load is the latent heat of fusion required to melt ice.

Electrothermal storage designed to return input energy back to electricity is only available for large scale systems where molten salt is used as a storage medium from which steam is generated to drive turbines.

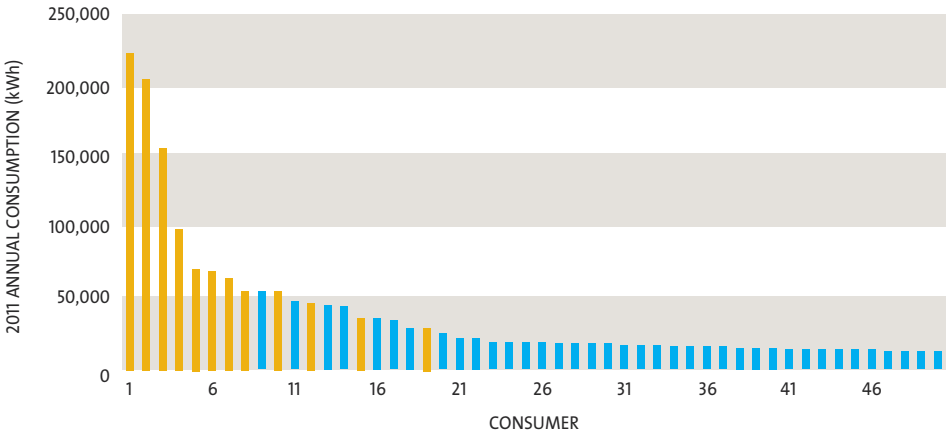
9.5 LOAD MANAGEMENT – DALY RIVER PRELIMINARY INVESTIGATION

As mentioned in Section 7.3.5 Load control, the use of load management can introduce operating/operational efficiencies into a hybrid power system and allow for greater solar penetration. Following is an overview of the results of the Daly River preliminary load management investigation. The overarching objective of the preliminary investigation was to determine if load management (direct control and interruption) should be further pursued as way of optimising the performance of a hybrid solar/diesel power station at Daly River.

Study context

There are 145 electricity customers in Daly River and in 2011, the total metered consumption was approximately 2 510MWh. The combined annual consumption of the top 19 commercial electricity customers, who represent 11.7 per cent of all electricity customers, was 1 395MWh, which equates to 55.6 per cent of the total electricity consumed in 2011. Out of the top 19 commercial electricity customers identified, 12 were involved in the preliminary investigation. These customers were a mix of government facilities, local council facilities and private commercial enterprises. The total consumption of these 12 facilities in 2011 was 1 104MWh, which represents 44 per cent of the total consumption.

Largest 50 electricity customers in Daly River (2011) with those surveyed in yellow.



Study approach

When the Daly River Solar Research Project was launched in July 2012, the Daly River community was provided with a project factsheet, outlining the project objectives and noting that PWC would be inviting commercial customers to participate in the research.

In December 2012 customers identified as possible participants in the investigation were contacted via phone prior to the site visits, to provide to inform them of the research objectives and determine willingness to be involved in the site visits. Where possible, the manager or owner of the facility was contacted. In this initial conversation the overall project was described, along with the specific objectives of the load management investigation and the planned site visit. The customers were asked for an initial commitment to a site visit time. Around one week ahead of the community visit, a second phone call was made to confirm the site visit and availability of the manager or owner.

Site visits were conducted at the premises of 12 participating customers. The objectives of the site visits were to understand the views of the customers about the concept of load management and the notion of PWC controlling the operation of select appliances (via the Daly River power station control system) and to collect data on specific consumer appliances which could potentially be used in a future load management trial.

During the site visits, high-power appliances at consumer premises were identified. Data was collected on the high-power appliances which may be able to be switched off for brief periods without impacting on the customers' level of comfort or service. The rated power for the devices was noted from equipment labels, but where these were not visible or present, the load was estimated by the consultant based on similar equipment. Appliance usage patterns were also discussed with customers; including whether the appliance was in use all year or seasonally or for certain periods of the day. The consumer was also asked about their overall patterns of power use.

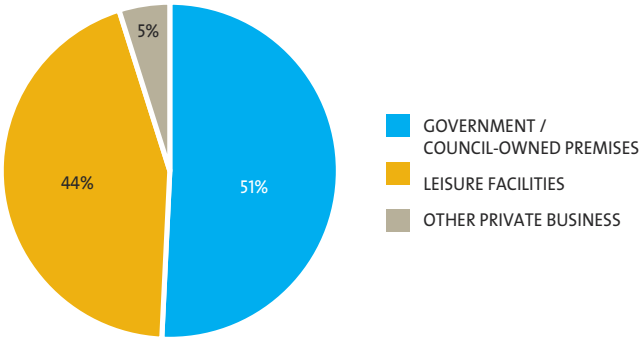
During the site visit, customers were also asked survey questions to determine their willingness to participate in a potential load management trial. The survey included their views on solar power, load management and whether an incentive would be required to encourage them to participate in a future trial.

Customers were provided with energy and water efficiency information and PWC merchandise during the site visits.

Following the visits and analysis of the survey and load management assessment results, follow-up letters and a factsheet were sent out to participants. The letter outlined some brief recommendations for energy efficiency improvements which were noted during the visit. The factsheet included preliminary findings from the initial investigation and next steps.

Daly River Load management – preliminary indications of potential by customer-type.

Diversified load, available for Load Management (kW)



9.6 LOAD MANAGEMENT – TECHNOLOGIES

Applying load management techniques for optimising renewable energy integration is an emerging field. The following is a description of equipment, currently available in the marketplace, which would be capable of controlling loads in a load management network for the specific application of optimising solar resource. While, the information below may quickly be superseded it should provide a useful initial starting point for investigations.

A complete system for load control in a load management network would comprise the following key elements:

- hardware and software located at the load management network operator's premises, capable of receiving input data (from the power station, the networked loads etc.) and producing programed output to the load management network appliances
- hardware located at the consumer's premises, capable of switching an individual appliance or a complete circuit on and off
- communications technology to transmit (wired or wireless) signals between the hardware at the operator's and consumer's premises.

The following is a brief outline of some prominent types of hardware and/or software packages currently available:

Residential energy management devices – appliance controllers: for example, 240V load control switches that also have energy consumption measurement capability. These are often remote-controllable via local radio communication and suitable for appliance-level load control.

Devices capable of circuit level control and monitoring: the load switching device connects directly into the switchboard to control all appliances on a single circuit.

Smart-grid-enabled air-conditioning thermostats: these devices may be capable of responding to radio and internet communication signals as part of a load management network. They are specifically targeted at replacing remote controls for room air-conditioners.

Utility level platforms: these include user control software, data handling controller and load control units for switching and metering.

For a comprehensive list, the International Energy Agency maintains a detailed database of currently available products: www.ieadsm.org/TaskXVNetworkDrivenDSMLoadManagementDatabase.aspx.

There are also various load management communication technologies. Each has advantages and disadvantages. To provide an optimal solution, often several technologies work in unison. The following is a short overview of some of these technologies:

Ripple control is a very common form of load control that has been available for a long time. It is most commonly used to control off-peak hot water or space-heating systems. It works by superimposing a higher-frequency signal (usually between 100 and 1 600Hz) onto the standard 50Hz power supply. When the signal is received by devices connected to the controllable load, they switch off the load until the signal is disabled or another frequency signal is received.

Traditionally, ripple control has been a one-way system, but more recently two-way systems are also being implemented where the consumer devices send information back to the utility, such as for billing purposes. Ripple control has a high capital cost but relatively low operating and maintenance costs.

A related technology is **power-line carrier**, which uses the power lines (conductors) as a means to establish a network, over which protocols such as TCP/IP or X10 can be used to communicate with devices, i.e. a Local Area Network (LAN) over power lines. This works more readily in a bi-directional fashion than ripple control. It is more commonly used within buildings than across distribution networks because of the absorption of the signal in transformers.

Traditionally, **telephone based systems** use dial-up modems, where the central control device can connect to a remote load via modem. Various communication protocols are possible over the modem link, to achieve different tasks. A more modern version of this uses mobile phone system based modems (GSM, 3G or 4G).

These systems are effective when communications are only required sporadically, such as downloading data from a power meter once a month. Systems have a modest capital cost (provided the phone line or mobile phone system is already in place at the consumer end) however can have a high operating cost, especially if communication has to occur frequently or to many customers at the same time.

As it is a one-to-one form of communication, it is less suitable for load control across a larger number of customers at the same time. There is also a substantial lead time in establishing communication to the end device (dialling, answering and responding). Traditionally this technology uses analogue signals, which limit the maximum throughput and reliability of the system.

Another technology that uses the wired phone system in a more advanced way is that of **ADSL**, which is how the majority of households receive their internet connection. More modern installations can use an optic fibre link which has a higher possible throughput than ADSL which is over copper wire.

The advantage of both of these types is they are an 'always on' system, so no 'dial-up' is needed when a communication is required. It is therefore also ideally suited as a communication channel for demand control.

While wired technologies have traditionally been considered to be more secure than wireless technologies, this distinction has been more or less removed with the availability of excellent encryption algorithms, particularly for digital signals.

Radio Frequency based systems work by having transmitters and receivers in various locations that communicate with each other by radio waves. These can be WiFi (2-5GHz), Bluetooth (2.4GHz), ZigBee (800MHz – 2.4GHz), UHF (~477MHz), FM (~100MHz) or similar based systems.

Often the devices comprise a transmitter and receiver in one unit (transceiver), thus easily enabling bi-directional communication. Most of these use digital transmission protocols and are thus readily compatible with current technologies.

Depending on the transmission frequency (and power level) the systems are suitable for shorter or longer distance transmissions, with UHF and FM for longer distance applications and higher frequency transmission systems for shorter distance applications. The capital cost varies depending on the power level and complexity of the system. The maintenance costs can be high, especially when devices have to be tested on site, requiring staff to travel to the remote sites. The cheaper devices are often discarded and replaced if they fail.

The **ZigBee** specification is intended as a low-cost, low-power, low-data transmission system. Data transmission can occur over distances of 15 to 150m (depending on the building's construction) but in a mesh network fashion. This means that rather than all end devices needing to communicate to a central hub or gateway, individual downstream devices can act as routers and pass the signal on to other devices in the vicinity, thus extending the physical range of the network without requiring higher power levels.

Transmission and reception within a ZigBee network are synchronised. This means the radios can be off much of the time and thus conserve power. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other Wireless Personal Area Networks (WPANs), such as **Bluetooth** or **Wi-Fi**.

More and more appliances are now manufactured with a ZigBee-compatible transceiver built in, such as in refrigerative airconditioners and some hot water systems. There are also many add-on devices available that essentially act as a switch or measurement device that communicates via the ZigBee specification to the network and is hard-wired to the device to be controlled. This makes ZigBee-based networks increasingly popular to use as demand management tools at a customer level, both for utility- and customer-initiated actions.

Contact us

Call 1800 245 092
Email customerservice@powerwater.com.au
Visit powerwater.com.au
Follow PowerWaterCorp on Twitter
ABN 15 947 352 360

Head office

Level 2, Mitchell Centre
55 Mitchell Street, Darwin
GPO Box 1921
Darwin NT 0801

Customer service centres

Shop 28, Ground Floor, Mitchell Centre
55 Mitchell Street, Darwin

Shop 21, Palmerston Shopping Centre
10 Temple Terrace, Palmerston

Ground Floor, Government Centre
5 First Street, Katherine

Shop 8, Alice Plaza
36 Todd Mall, Alice Springs

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